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EAST PORTAL OF TOOTH ROCK HIGHWAY TUNNEL, OREGON

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D. M. BEACH, *Editor*

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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HIGHWAY TUNNELS IN WESTERN STATES

BY THE REGIONAL OFFICE, UNITED STATES BUREAU OF PUBLIC ROADS[1]

TUNNELING is one of the oldest construction activities of man. The Assyrians constructed a tunnel under the Euphrates River with a cross section 12 feet wide by 15 feet high. The Romans employed tunnels in their highways. Near Naples a 3,000-foot tunnel was excavated and the lighting problem was given skillful attention. The width of the tunnel was about 21 feet throughout, but the height was increased from 25 feet at the center to 75 feet at the portals, thus to a degree aiding its illumination in daylight. In the Middle Ages tunneling continued in fortification works and in aqueducts, of which the Languedoc and St. Quentin canals in France are outstanding examples.

Modern times have witnessed the construction of a great many railroad and water tunnels. The outstanding railroad tunnel is the Simplon connecting Italy and Switzerland through the Alps, and is 12.4 miles long. It was bored under great difficulties, one of the main obstacles being the heat that resulted from the excessive depth of cover. Other important railroad tunnels are the Mount Cenis, France to Italy; St. Gothard, in Switzerland; Hoosac, in Massachusetts; Rogers Pass, in British Columbia; and the Moffat, in Colorado.

The greatest advances in modern tunneling methods were achieved through the introduction of compressed air and the development of high explosives.

Modern traffic demands highways that can be traveled with speed and safety. In the mountainous parts of the west provision is being made for speeds of 45 to 50 miles per hour, and economy in design has resulted in the construction of some 35 tunnels. Table 1 gives dimensions, cost, and design details. Figures 1 and 2 illustrate typical cross sections of these tunnels.

Ventilation problems have not developed in most of these tunnels, as nearly all of them are less than 1,000 feet long. Consideration had to be given to ventilation in the East Rim Road tunnel in Zion National Park, 5,613 feet long; in the Wawona tunnel in Yosemite National Park, 4,233 feet long; and in the Broadway Low Level tunnel, between Alameda and Contra Costa Counties, Calif., 3,203 feet long.

The numerous galleries introduced for ventilation in the East Rim Road tunnel served the further purpose of affording the traveler incomparable vistas. These galleries solved the ventilation problem, but with additional cost for heavier lining. The faces of the cliffs in Zion National Park are vertical, and are of extreme height. They are composed of sandstone in horizontal beds. These faces undergo extreme temperature changes and constantly expand and contract, thus developing temperature relief joints. These joints or cracks are both normal and parallel to the faces of the cliffs and extend back some distance from the face. A tunnel located well back from the face would undoubtedly be in entirely self-supporting rock, requiring less lining but more artificial ventilation.

The Tooth Rock tunnel in Oregon, is a model in landscape finish and lighting. The four-lane tunnel on the north approach to the Golden Gate Bridge, and the double-deck, six-lane Yerba Buena Island tunnel connecting the San Francisco-Oakland Bay Bridges are interesting to American engineers because the German system of headings was used in their excavation. (See fig. 3.)

Operations in the Broadway tunnel were of special interest. During construction, temporary timber sets that gave signs of distress, were reinforced solidly for full depth by cement mortar applied by means of a pneumatic cement gun.[2] Louvers introduced in this project for light diffusion by forming a transition at the portals were also unique.

The Willamette tunnel in Oregon, while of moderate length, is bored upon a curve of 4°36′, the curved inner sidewalk being taken into consideration in providing adequate sight distance. This design differs from the usual practice in the west of locating tunnels on tangents, although in the Broadway tunnel reverse curves are incorporated at the ends in order to spread the spacing of the bores from 15 feet at the portals to 100 feet for the major portion of their lengths. The spacing is essential in twin bore tunnels as a safety provision in blasting during construction. Steel lining for highway tunnels was first used in the west in the Ventura-Maricopa tunnels.

TUNNELS HAVE SEVERAL ADVANTAGES OVER OPEN-CUT CONSTRUCTION

It has been the policy of the Bureau to consult with a geologist regarding the rock formations that can be expected to be encountered in the construction of major tunnels. The geologists' advice should be followed as to the extent and character of preliminary exploration work. On a few tunnels the practice has been to open the faces as a part of the location work, and in one instance short preliminary headings were excavated to determine the uniformity of the material.

Where the geologist is in doubt, a preliminary classification using the seismographic method is warranted. The obtaining of seismographic profiles should reduce the number of exploration borings to a minimum.

The question of whether to construct a tunnel or an open cut at a particular location should be decided only after careful study of the probable costs of constructing and maintaining each. Three principal advantages of tunnels over open cuts are:

1. Tunneling generally enables better location and design by reducing curvature and length and hence contributes to highway safety.
2. If special facilities for ventilation and lighting are not required, tunneling reduces maintenance costs and in any event practically eliminates snow removal costs.
3. Tunneling reduces scar (a landscape item), and eliminates erosion.

The necessity of portal structures is a major factor in determining the minimum length of tunneling where critical depths of cover are encountered. Assuming the average cost of portals to be $4,000 each, with the critical depth of cover between 80 and 100 feet the economical minimum length of tunnel, depending upon average excavation and lining costs, would be in excess of 80 feet.

[1] This report was prepared by engineers of the regional office of the Bureau in San Francisco, Calif., with special assistance as noted.

[2] "Pneumatically applied mortar" is a mixture of portland cement and sand, mixed dry in proportions of 1 sack of cement to 4 cubic feet of sand. It is forced by air through a flexible tube to a nozzle where the mixture is hydrated and discharged by pneumatic pressure against the surface being treated.

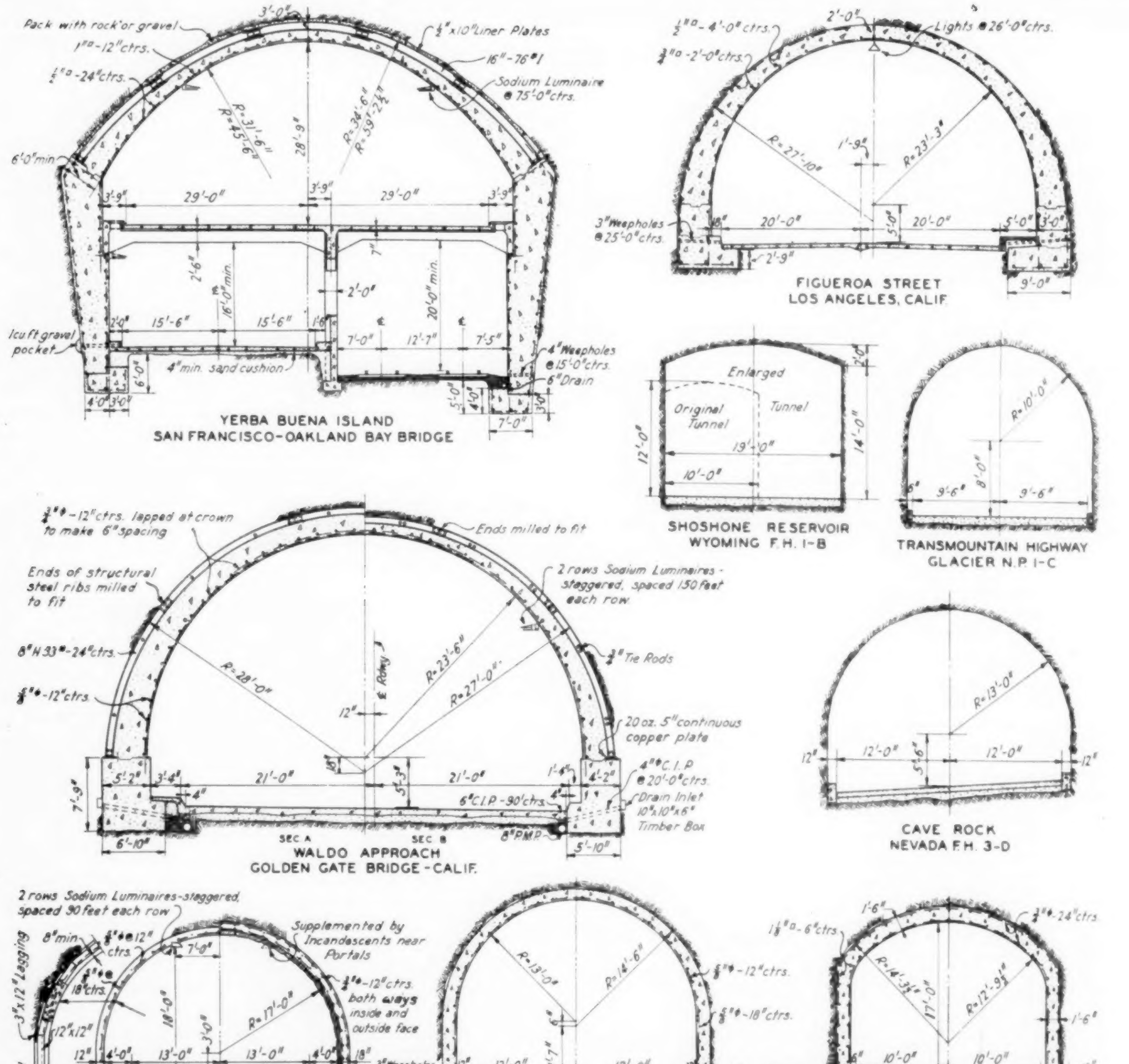

FIGURE 1.—CROSS SECTIONS OF SEVERAL HIGHWAY TUNNELS CONSTRUCTED IN THE WESTERN STATES.

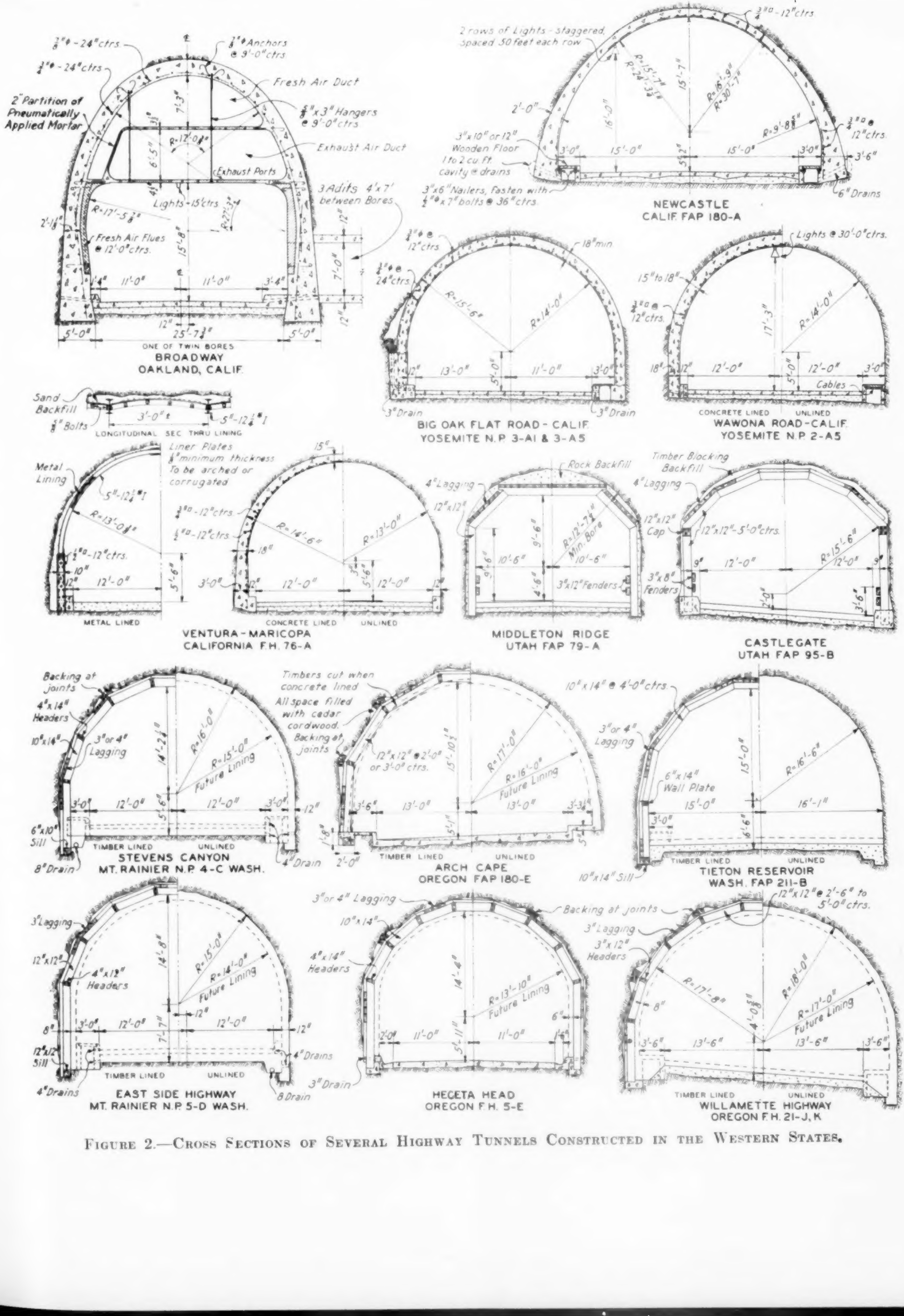

FIGURE 2.—CROSS SECTIONS OF SEVERAL HIGHWAY TUNNELS CONSTRUCTED IN THE WESTERN STATES.

TABLE 1.—*Dimensions, costs, and other*

TUNNELS CONSTRUCTED UNDER DIRECTION

Tunnel	Location	State	Length (feet)	Year constructed	Material encountered	Type of lining	Portal structures
Wawona Road, Project 2-A5.	Yosemite National Park.	California	4,233	1932-33	Solid granite and diorite.	Reinforced concrete and pneumatically applied mortar.	One, reinforced concrete.
Big Oak Flat Road, Project 3-A1.	Yosemite National Park.	California	2 tunnels 187 and 353, total 540.	1936-38	Granite (solid and altered).	Reinforced concrete	Four, cement rubble masonry.
Big Oak Flat Road, Project 3-A5.	Yosemite National Park.	California	2,167	1936-38	Granite	Reinforced concrete	None to date
Ventura-Maricopa, forest highway, Project 76.	North of Ventura	California	3 tunnels 170, 128, and 206, total 504.	1931	Shattered shale and serpentine.	Reinforced concrete and steel plate.	Five, reinforced concrete.
Burns Summit, forest highway, Project 7-D.	East of Couer d' Alene.	Idaho	394	1931-32	Talc, shale	Reinforced concrete	Two, reinforced concrete.
Shoshone Reservoir, forest highway, Project 1-B.	West of Cody	Wyoming	4 tunnels 165, 132, 30, and 15, total 342.	1926		None	None
Trans-Mountain Highway, Glacier National Park, Project 1-C.	Glacier National Park.	Montana	187	1926-27	Limestone	None	None
Cave Rock, forest highway, Project 3-D.	East shore of Lake Tahoe.	Nevada	151	1931	Granite	None	None
Heceta Head, forest highway, Project 5-E.	Coast highway	Oregon	680	1930	Clay, boulders, rock	Timber	
Toothrock, Forest Highway Project 28-A.	Columbia River highway.	Oregon	828	1936-37	Basalt	Reinforced concrete	Reinforced concrete
Willamette Highway, Forest Highway Project 21, JK.	Southeast of Eugene.	Oregon	875	1937-38	Granite	Portions with reinforced concrete.	None to date
Mt. Rainier National Park, Project 5-D.	Eastside highway	Washington	510	1937-38	Shattered rock	Timber	
Mt. Rainier National Park, Project 4-C.	Stevens Pass route.	Washington	285	1937-38	Solid rock	None	
Zion National Park, Project 1-A2.	East Rim road	Utah	5,613	1927-36	Sandstone	Concrete, pneumatically applied mortar.	One, cement rubble masonry.
Zion National Park, Project 1-A3.	East Rim road	Utah	488	1927-36	Sandstone	Gunite	None

TUNNELS CONSTRUCTED UNDER DIRECTION

Tunnel	Location	State	Length (feet)	Year constructed	Material encountered	Type of lining	Portal structures
Superior-Miami, Federal Aid Project 16.	Superior - Miami highway.	Arizona	277	1919-22	Granite	None	None
Newcastle, Federal Aid Project 180-A.	Newcastle	California	531	1931-32	Granite	Reinforced concrete	Reinforced concrete
Waldo, State Project IV-Marin-1D.	North approach to Golden Gate Bridge.	California	1,000	1957	Shattered shale	Reinforced concrete	Reinforced concrete
Arch Cape, Federal Aid Project 180-E.	South of Seaside	Oregon	1,278	1936-37	Sandstone, shale	Timber	
Cooks-Underwood, Federal Aid Project 112-F.	East of Cooks	Washington	261-No. 1 212-No. 2	1936	Lava	Reinforced concrete	Reinforced concrete
Cooks-Underwood, Federal Aid Project 112-H.	East of Cooks	Washington	130 408 257	1936-37	Lava	Reinforced concrete	Reinforced concrete
Tieton Reservoir, Federal Aid Project 211-B.	West of Yakima, White Pass.	Washington	615	1936-37		Timber for 50-foot each end.	Cement rubble masonry.
Castlegate, Federal Aid Project 95-B.	Near Castlegate	Utah	410	1931	Shale, some coal	Timber	Reinforced concrete
Middleton Ridge, Federal Aid Project 79-A.	East of St. George.	Utah	237	1926-27	Sandstone	Timber	Reinforced concrete

[1] Includes cost of curbs—$3 per foot.

data on western highway tunnels

OF BUREAU OF PUBLIC ROADS

Cost per portal (dollars)	Dimensions of tunnel section	Total tunnel cost (dollars)	Costs per foot for— Unlined tunnel (dollars)	Lining (dollars)	Lined tunnel (dollars)	Unit costs for principal construction items	Remarks
....	24-foot roadway, 19-foot center height, 1 3-foot walk.	528,200	....	....	125	Driving main tunnel, $80 per lineal foot. Reinforced concrete lining, $50 per lineal foot. Pneumatically applied mortar lining, $30 per cubic yard.	Tunnel costs include portal costs and adit costs, also lighting and ventilation equipment installation; pavement cost excluded.
2,775	24-foot roadway, 19-foot center height, 1 3-foot walk.	129,000	77 and 102	145	240	Driving pioneer bore, $18.44 per lineal foot. Enlarging to size, $66.03 per lineal foot. Concrete lining, $21 per cubic yard. Cement rubble masonry, $34.49 per cubic yard.	Tunnel costs exclude portal and paving costs.
....	24-foot roadway, 19-foot center height, 1 3-foot walk.	257,500	119	....	....	Tunnel driving, $108 per lineal foot. Adit driving, $20 per lineal foot.	Tunnel costs include: Temporary timbering, pneumatically applied mortar lining, 6- by 7- by 107-foot adit.
1,570	24-foot roadway, 18-foot 6-inch center height, no walks.	62,630	1 67	*Reinforced concrete* 95 *Steel plate* 46	 165 116	Lined tunnel, $70 per lineal foot. Unlined tunnel, $64 per lineal foot. Reinforced concrete lining, $95 per lineal foot. Steel plate lining, $46 per lineal foot.	Tunnel costs exclude portal costs.
2,196	20-foot roadway, 17-foot center height, no walks.	97,000	....	....	245	Tunnel excavation, $60 per lineal foot. Reinforced concrete lining, $106.90 per lineal foot. Reinforcing steel, $0.06 per pound. Concrete, $30 per cubic yard.	Tunnel costs exclude portal costs.
....	19-foot roadway, 16-foot center height, no walks.	8,208	24	....	....	Enlarging to size, $24 per lineal foot	Cost of enlarging only from 10- by 12-foot tunnels to 19- by 16-foot size.
....	19-foot roadway, 18-foot center height, no walks.	22,515	120	....	....	Tunnel excavation, $6 per cubic yard	
....	24-foot roadway, 18-foot 6-inch center height, no walks.	13,600	90	....	....	Unlined tunnel, $90 per lineal foot	Concrete curbs not included in tunnel cost.
....	22-foot roadway plus 2 1-foot 6-inch gutters, 20-foot center height, no walks.	60,700	....	....	88	Tunnel excavation, $66.50 per lineal foot. Timber, $55 per thousand feet board measure.	Curbs not included.
6,400	26-foot roadway, 20-foot center height, 2 4-foot walks.	177,385	....	....	214	Tunnel excavation, $85 per lineal foot. Concrete, $22.50 per cubic yard. Timber, $55 per thousand feet, board measure. Cement rubble masonry, $12 per cubic yard.	Tunnel cost includes lighting system installation for $6,680.
....	26-foot roadway, 21-foot center height, 2 3-foot 6-inch walks.	91,475	80	....	152	Unlined tunnel, $80 per lineal foot. Lined tunnel, $100 per lineal foot. Timber, $65 per thousand feet, board measure.	300-foot reinforced concrete lining. 575-feet unlined.
....	24-foot roadway 21± -foot center height, 1 3-foot walk.	69,400	....	....	136	Tunnel excavation, $89 per lineal foot. Timber, $60 per thousand feet, board measure.	Change order during construction will modify costs considerably.
....	24-foot roadway, 20± -foot center height, 1 3-foot walk.	26,180	92	....	....	Tunnel excavation, $90 per lineal foot	Timbering omitted.
4,000	20-foot roadway, 16-foot center height, no walks.	790,628	....	....	140	Driving tunnel, $55 per lineal foot. Pneumatically applied mortar, $24 to $26 per cubic yard. Concrete lining, $50 per lineal foot. Reinforcing steel, $0.04 to $0.05 per pound.	Costs include galleries. Costs not segregated between lined and unlined portions.
....	20-foot roadway, 16-foot center height, no walks.	31,130	....	....	64	Driving tunnel, $55 per lineal foot. Pneumatically applied mortar, $26 per cubic yard.	Lined with pneumatically applied mortar only.

OF STATE HIGHWAY DEPARTMENTS

Cost per portal (dollars)	Dimensions of tunnel section	Total tunnel cost (dollars)	Unlined tunnel (dollars)	Lining (dollars)	Lined tunnel (dollars)	Unit costs for principal construction items	Remarks
....	2 lanes, no walks	16,032	58	....	....	Tunnel excavation, $6 per cubic yard	
3,500	30-foot roadway, 20-foot 9-inch center height, 2 3-foot walks.	126,300	....	....	238	Tunnel excavation, $120 per lineal foot. Reinforced concrete lining, $110 per lineal foot.	Tunnel cost includes installation of electric lighting system for $1,500.
7,500	42-foot roadway, 28-foot 9-inch center height, 1 3-foot 4-inch walk.	483,500	225	258	483	Tunnel excavation, $4.40 per cubic yard. Reinforced concrete lining, $220 per lineal foot. Reinforced concrete lining, $165 per lineal foot. Reinforcing steel, $0.055 per pound.	Installation of lighting system, $2,160.
....	26-foot roadway, 21-foot center height, 2 3-foot 6-inch walks.	200,138	....	....	157	Tunnel excavation, $3.50 per cubic yard. Timber, $70 per thousand feet, board measure.	Future reinforced concrete lining.
3,110-No. 1 870-No. 2	24-foot roadway, 20+ foot center height, no walks.	No. 1–56,982 No. 2–27,270	....	....	218 129	Tunnel excavation, $4 per cubic yard. Concrete, $16 and $18 per cubic yard. Reinforcing steel, $0.05 per pound.	High cost of tunnel No. 1 due to cave-in on adjacent railroad tunnel caused by highway tunnel construction.
1,160 1,335 1,770	24-foot roadway, 20+ foot center height, no walks.	15,632 52,645 43,837	....	....	120 124 171	Tunnel excavation, $3.88 per cubic yard. Concrete $16.50 per cubic yard. Reinforcing steel, $0.05 per pound.	High cost of tunnel lining in No. 3 due to increased thickness of lining.
1,850	24-foot roadway, 21-foot center height, 1 3-foot walk.	65,600	114	38	162	Tunnel excavation, $4 per cubic yard. Timber, $80 per thousand feet, board measure. Cement rubble masonry, $18 per cubic yard.	
1,815	24-foot roadway, 17-foot 6-inch center height, no walks.	38,400	....	....	95	Tunnel excavation, $60 per lineal foot. Timber lining, $60 per thousand feet, board measure. Concrete, $18 per cubic yard plus cement at $0.82 per sack.	
1,800	20-foot roadway, 14-foot center height, no walks.	20,400	....	....	86	Tunnel excavation, $48 per lineal foot. Concrete, $27.50 per cubic yard plus cement at $0.83 per sack. Timber, $110 per thousand feet, board measure.	

TABLE 1.—*Dimensions, costs, and other*
TUNNELS CONSTRUCTED UNDER

Tunnel	Location	State	Length (feet)	Year constructed	Material encountered	Type of lining	Portal structures
Broadway Tunnel	Oakland	California	Twin bores 3,203 and 3,135.	1934-37	Shattered shale	Reinforced concrete	Monumental reinforced concrete.
Yerba Buena Island	San Francisco-Oakland, Bay Bridge.	California	540	1936-37	Shattered shale	Reinforced concrete	Monumental reinforced concrete.
Figueroa Street Extension.	Los Angeles	California	3 tunnels 46, 130, 405	1936		Reinforced concrete	Reinforced concrete

Photo by the California Toll Bridge Authority.

FIGURE 3.—THE YERBA BUENA ISLAND TUNNEL, CALIFORNIA, ILLUSTRATING THE GERMAN METHOD OF TUNNELING.

For short tunnels on tangents the brief time required to pass through the tunnel and the infiltration of light from the portals remove the necessity for lighting at the portals.

Where tunnels 1,500 feet or longer are required, or where vertical curves which might create gas pockets are encountered, provision must be made for ventilation. It has been the policy of the Bureau of Public Roads to consult with the United States Bureau of Mines on ventilation problems in the design of the major tunnels it constructs. Natural ventilation, from differences in barometric pressure, is generally unreliable. However, carbon monoxide, which is the principal gas that must be removed from tunnels, is lighter than air, and when heated is much lighter than cool air. It therefore tends to flow upward along the top of the tunnel, especially if the location is on a continuous grade.

Under usual conditions a composite [3] car will exhaust carbon monoxide on grades of 4 percent or less at a rate of 1.5 cubic feet per minute per car. Assuming 2 cubic feet per minute and assuming 2 parts in 10,000 to be the maximum concentration allowable, provision must be made for supplying 5,000 cubic feet of fresh air per minute per car. Using "transverse" ventilation, on tunnels over 3,000 feet long, considerable tunnel space is required for the large air ducts needed to provide for the peak traffic. In transverse ventilation the fresh air is blown in through ducts having ports, generally at the same elevation as the seats of passenger cars, spaced at regular intervals along the walls, and exhausted through a crown duct. This system is not widely used in tunnels in rural locations. The transverse system is not, of course, adapted to use in unlined tunnels.

In the "longitudinal" ventilation system the necessity of ducts is eliminated if adits or shafts can be strategically introduced as provided, for example, in the design of the Wawona tunnel in Yosemite National Park. In this ventilation system provision is made to exhaust the contaminated air at a point or points along the bore through shafts or adits, the fresh air entering through the portals or through adits or shafts acting in conjunction with the portals. The longitudinal ventilation system can be used on any length of tunnel, provided openings are constructed at intervals not more than ½ mile apart. Under such conditions, ventilation is an important economic factor in respect to both first cost of installation and operating charges.

A combination of the transverse and longitudinal ventilating systems might be economical in tunnels of moderate length where shafts and adits are not feasible. Under a combination design, the gas would be exhausted along a crown duct, while the fresh air would come in through the portals, using the roadway area. No additional fresh air duct would be provided as in the case of the transverse ventilation system.

Advocates of the transverse system claim that it is superior in localizing a fire by preventing the smoke and flame from traveling along the bore. The accuracy of this assumption is very doubtful in the case of a major conflagration, since a tunnel, especially one on a grade, would probably act as a chimney under either the transverse or longitudinal system. Under the above emergency, after all individuals had been rescued, the fans should be stopped to avoid possible heat damage to the fans and other equipment. Stopping the fans would also help to smother the fire. A better control probably would be the installation of fire doors.

[3] The "composite" car used in the design of a tunnel ventilation system should be representative of the traffic expected to use the tunnel. That is, it should produce the same amount of contamination as the average vehicle using the tunnel.

data on western highway tunnels—Continued

DIRECTION OF OTHER AGENCIES

Cost per portal (dollars)	Dimensions of tunnel section	Total tunnel cost (dollars)	Costs per foot for—			Unit costs for principal construction items	Remarks
			Unlined tunnel (dollars)	Lining (dollars)	Lined tunnel (dollars)		
Not segregated.	Each bore 22-foot roadway, 15-foot 8-inch center height, 1 3-foot 4-inch walk.	Original estimate 4,173,000.			1,320	Driving tunnel, $325 per lineal foot. Ventilating, lighting for $785,000.	Costs include driving, lining, paving, etc. Constructed by Joint Highway District No. 13.
Not segregated.	Upper deck, 58-foot roadway, 29-foot center height, 2 3-foot 9-inch walks. Lower deck-truck lane, 31-foot roadway, 16-foot center height. Railroad space, 27-foot horizontal, 20-foot height.	851,453			1,580	Original lump sum bid $610,000 for all items increased by changes to $851,435.	Constructed by California Toll Bridge Authority and State Division of Highways.
No data	40-foot roadway, 28-foot 3-inch center height, 1 5-foot walk.	541,166			543	Tunnel costs include all items of construction, driving, lining, paving, portals, etc.	Constructed by local improvement district.

PERMANENT LINING FREQUENTLY NEEDED IN TUNNELS

In adopting a cross section for tunnels, even in self-supporting rock formations, experience indicates that sufficient area should always be provided for a minimum thickness of lining.

In adopting a cross section for rural tunnels, it must be borne in mind that excavation for a tunnel in rock formation will, in general, cost about $5 per cubic yard. Also, a vertical clearance of 14 feet is desirable. This vertical clearance generally makes it economical to design with a semicircular intrados section with the springing lines from 3 to 5 feet above the pavement grade. This form of section allows space for at least 3-foot sidewalks with no infringement of clearance on traffic lane widths.

At best, lighting conditions at tunnel portals are not ideal and ample roadway is, therefore, essential. Some of the older vehicular tunnels have meager widths. The travelway of the East Rim Road tunnel in Zion Nation Park (see figure 1) is only 20 feet. In newer tunnels the travelways are wider; for example the Wawona tunnel travelway is 24 feet wide; the Tooth Rock tunnel travelway is 26 feet wide; and the Willamette tunnel, which is on a curve of 4°36′, has a travelway 27 feet wide. The Waldo four-lane tunnel has a 42-foot, four-lane travelway and one 3½-foot sidewalk. With regard to the East Rim Road tunnel's narrow section, it should be noted that the tunnel is within a National Park and the traffic moves slowly to take advantage of the vistas afforded from the tunnel's several galleries.

In designing timber lining sets, there is generally a choice between 5 to 7 segments (see fig. 4) and the use of a wall plate between the posts and the first segments. Where sets are not to be removed when permanent lining is placed, wall plates should be omitted. In ground that requires driving with side headings at the springing lines (see fig. 5) it is generally easier to keep the segments true to section if side plates are used. These plates are difficult to remove when setting posts as the core is excavated, and should be omitted if possible.

Mud sills are generally needed under the footings of posts, but where posts are notched into rock formations, blocks to give uniform bearing are equally serviceable. Their function is to provide even bearing and prevent kicking in at the bottom. It has been the general practice to design sets with untreated timber, using 12- by 12-inch material for plates, posts, and mud sills.

Figure 4.—The Arch Cape Tunnel, Oregon, With Timber Lining in Place. The Lining Sets Consisted of Five Segments, Wall Plates, and Posts.

Headers, 4 by 12 inches, with 3- or 4-inch lagging are required.

As a safety measure in heavy ground and as a temporary item during construction, horizontal cross struts or square sets are usually required. (See figs. 6 and 7.)

Timber sets designed for the Stevens Canyon-Mount Rainier National Park tunnel (see fig. 2), where the sets were expected to serve for an extended period, consisted of 10- by 14-inch material fastened by 1- by 6-inch dowels at the joints. Longitudinal bracing consisted of 4- by 14-inch headers held with twentypenny spikes. The bottom of the post was set in rock channels on 6- by 10-inch blocks.

In packing the space behind and above the timber lining, (see fig. 8) it is generally the practice in forest areas to use the class of wood available locally. Over permanent lining hand-placed stone is desirable. In large cavities, sand can easily be pumped back of the concrete lining if pipes are placed for this purpose during concreting. (See fig. 9.) Sand can also be placed advantageously behind steel liner plates. Where the rock contains open cracks or faults sand will probably not be satisfactory, but lean concrete can be used to advantage. Sand was used successfully on the East Rim Road tunnel in a large overbreak section, and on the Maricopa-Ventura tunnel behind the liner plates on very thin sections.

In designing tunnel linings, considerable judgment

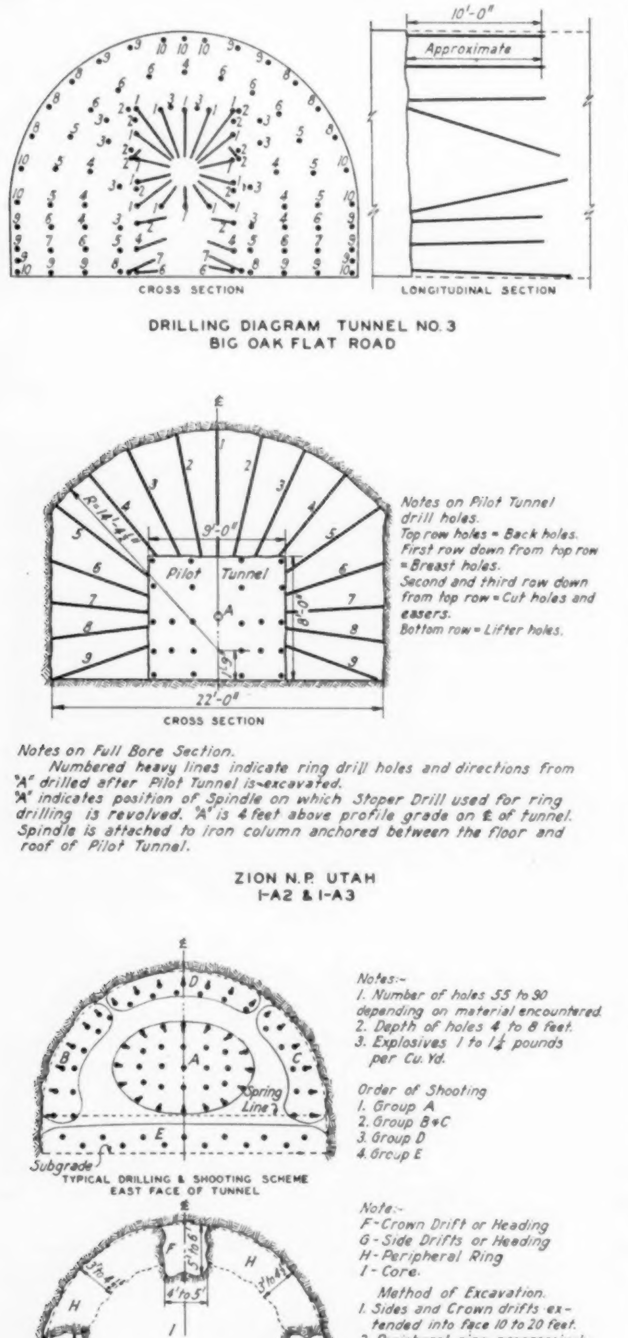

FIGURE 5.—DRILLING PLANS FOLLOWED IN THE CONSTRUCTION OF THREE WESTERN HIGHWAY TUNNELS.

must necessarily enter into the determination of crown depth. In earth formations, the depth of active overburden can be estimated with reasonable accuracy. Having determined the maximum depth of active overburden, the necessary thickness of lining can be calculated by applying the formulas used in designing other arch structures. E. Lauchli's work on tunneling gives a method of determining the thickness of lining based on measurements of crown deflection. Deflections at the crown in most rock formations would be so small that other considerations, in general, determine the minimum thickness of lining. In earth formations, it is best to make a very liberal allowance for the weight of the overburden to be carried by the lining. The theory of earth pressure deals with dry granular masses under ideal conditions, but where saturated soil is encountered, indeterminable conditions develop and considerable temporary timber lining becomes necessary before permanent lining can be placed. Under such conditions the performance of the temporary timber lining is generally a satisfactory guide in designing a permanent concrete or steel lining.

Generally, tunnels are needed only in rock formations, since mountains with soil cover are usually of such easy slopes as to make tunneling unnecessary. Rock masses are generally self-supporting and lining is only required to support shattered areas or to protect sections through fault planes.

Judgment based on experience with various geological formations must be used in estimating the maximum depth of rock fragment which might become detached and hence need support. Generally, 5 feet would be an ample depth, and if the lining is placed before fragments become loosened, there is quite a factor of safety by reason of the internal friction of the fragments before movement can begin. Calculations will ordinarily indicate a depth of lining much less than the minimum that can be efficiently placed by the best methods. Using concrete, a crown thickness of 12 inches is about the least that can be successfully placed in tunnel linings. A composite lining of steel plates, I-bars, and concrete, allows a very shallow depth of lining with a minimum of 8 inches at the crown.

Considerable portions of the Wawona and East Rim Road tunnels were entirely self-supporting, and a minimum thickness of pneumatically applied mortar was used to prevent raveling and weathering on some sections.

The East Rim Road tunnel was originally lined with pneumatically applied mortar over the self-supporting sections and timber was used on portions where needed. (See fig. 1.) Later this timber showed considerable distress due to the working of the cliff faces, and steel members were installed in the sections having the greatest movement. Ten-inch, 21-pound I-beams spaced 3 feet between centers and set in concrete have been sufficient to prevent any further movement.

PORTALS SHOULD HARMONIZE WITH SURROUNDINGS

The extensive use of pneumatically applied mortar in the Wawona tunnel produced a very pleasing finish. (See fig. 10.) This treatment softened the appearance of angular breakage of the rock.

Pneumatically applied mortar is especially adapted to irregular sections where form building would be difficult. In one gallery of the East Rim Road tunnel, application of the mortar solved a very troublesome problem. The roof of this gallery, which was very irregular in contour over its 100-foot span, gave indication, when sounded, that cracks were developing which might later allow sizeable fragments to fall. If an attempt had been made to fit lining forms, considerable dangerous and expensive trimming would have been necessary, and the long spans would have made stress determinations very difficult. The plan adopted was to grout 1-inch anchor rods to a depth of 9 feet. These rods were spaced 5 feet

between centers, and held by hooked ends a grillage of reinforcement made up of ½-inch rods spaced 12 inches between centers. This grillage was securely imbedded in a 6-inch slab of mortar placed by the pneumatic

FIGURE 6.—SQUARE SETS THAT FAILED BECAUSE OF HEAVY GROUND ENCOUNTERED, IN THE NORTH PACIFIC FOREST HIGHWAY TUNNEL, IDAHO.

FIGURE 7.—THE NORTH PACIFIC FOREST HIGHWAY TUNNEL, IDAHO, SHOWING PROGRESS IN REPLACING TIMBER SETS WITH CONCRETE LINING.

method. It has solved the problem economically and presents a very agreeable appearance.

In wet formations provision for tunnel drainage is necessary. Where saturated soil cover is encountered, tile should be used to convey the water through to the portals. Grouting rock seams is generally not satisfactory, but where a flow of water is present, tile should be laid behind the tunnel lining.

Tile should also be laid in the subgrade beneath the road surface. The area below the sidewalks is a convenient location for drainage and wiring facilities.

If water would tend to flow on the pavement into the portals, surface grillage drains should be located outside the portals, tranverse to the tunnel axis, and complete for the entire width of roadway.

Natural rock slopes at tunnel portals give a pleasing appearance, but some protective work is generally neces-

FIGURE 8.—UPPER, STEEL PLATE LINING IN THE MARICOPA-VENTURA TUNNEL, CALIFORNIA. LOWER, TOOTH ROCK TUNNEL, OREGON, SHOWING A HOLE OUTSIDE THE NEAT TUNNEL LINE BEING FILLED WITH WOOD.

sary, if portal structures are not used, to prevent drip and icicle formation which may become a traffic hazard.

In tunnels over 1,500 feet long, where the construction of galleries is impractical, some form of mechanical ventilation is necessary. In rural tunnels, the longitudinal system of ventilation will generally be found to be more economical. The fans should be placed far enough away from the roadway to be clear of any flame that might develop from burning oil tank wrecks. The exhaust adits or shafts should be so located as to draw gas from the upper area of the bore.

The ventilation machinery should operate automatically under normal conditions, and there should also be manual controls. It should also be capable of reversing the direction of air currents, as is possible in the Wawona tunnel.

The control room should not be within the tunnel, but should be located at a point where it will be quickly accessible in case of a fire within the tunnel. In case of a bad fire, the ventilation system could not be expected to handle all of the escaping smoke indefinitely,

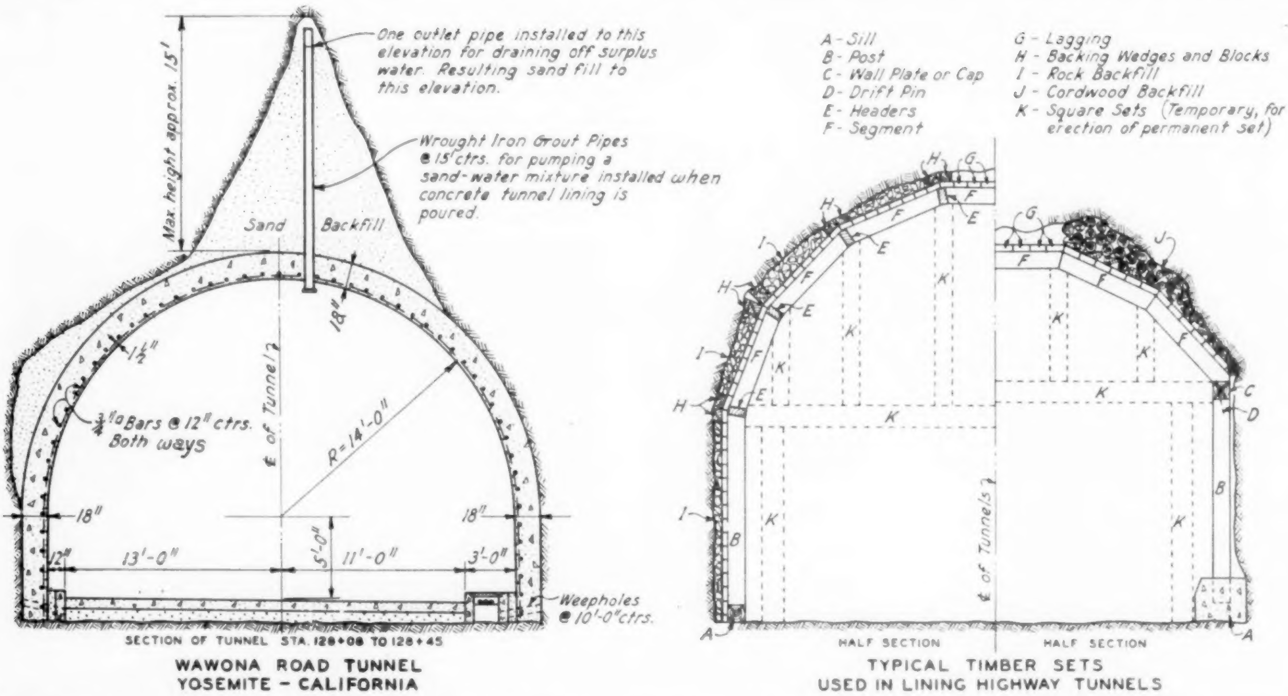

FIGURE 9.—LEFT; CROSS SECTION OF WAWONA TUNNEL, CALIFORNIA, SHOWING SAND BACKFILL ABOVE CONCRETE LINING. RIGHT; TYPICAL TIMBER SETS USED IN LINING HIGHWAY TUNNELS.

FIGURE 10.—PNEUMATICALLY APPLIED MORTAR BEING PLACED IN THE WAWONA TUNNEL, CALIFORNIA.

but only long enough to permit all travelers to escape from the tunnel.

The principal function of a tunnel portal is to support the weaker strata generally found at the ground surface. Portals generally reduce the length of the bore and the lining. From a landscape viewpoint they are not as attractive as natural formations (see fig. 11).

The portal design should be in keeping with the surrounding formations. The design of the lower portal to Maricopa-Ventura tunnel No. 3, while attractive (see fig. 12), could have been improved by introducing coloring material into the concrete mixture to darken the finish to the shade of the surrounding formations. The lining ring should be a shade lighter than the concrete work above the extrados.

The west portal of the Wawona tunnel (fig. 13) illustrates one method of portal treatment. The smooth portal harmonizes with the regular, even rock slopes

FIGURE 11.—EAST PORTAL OF THE EAST RIM ROAD TUNNEL, UTAH. STRONG, DURABLE, NATIVE ROCK AT THIS PORTAL MADE CONSTRUCTION OF A PORTAL STRUCTURE UNNECESSARY.

above the parapet. The curved extrados at the left accentuates the arched section of the tunnel, and gives the appearance of stability to the portal in sympathy with the formation of the adjacent cliff. This unobtrusiveness in line may be compared with the jagged appearance of the Big Oak Flat tunnel portal (fig. 14) where the masonry lines give much the broken effect of the shattered rock formations of the cover. The

curved line of the parapet also carries out the scheme of the tunnel arch.

The Tooth Rock tunnel portals have very pleasing appearances as may be observed in figure 15 and in the cover illustration. The arch of this tunnel is carried through in the curved upper line of the parapet. The long curve of the wing walls blends into the retaining walls. The slopes above the portal structure are to be stabilized and improved by appropriate planting of local shrubs. The broken lines of the masonry above the arch ring give the effect of informality.

In contrast to these rural tunnel portals are the monumental structures of the Yerba Buena tunnel of the San Francisco-Oakland Bay Bridge. (See fig. 16). It was fitting that the portals of this tunnel be in keeping with the entire project. They are not too much dwarfed by the adjacent towers of the spans, and the smooth concrete harmonizes with the longer lines of other parts of the project.

FIGURE 12.—PORTAL STRUCTURE OF THE MARICOPA-VENTURA TUNNEL, CALIFORNIA. THE STRUCTURE WAS NEEDED TO REINFORCE THE BADLY SHATTERED NATIVE ROCK.

In the future more attention will undoubtedly be paid to the lighting of highway tunnels, especially at the portals during the brighter portion of the day. Good lighting is necessary as a safety measure because of the slowness with which the eye adapts itself to a change from bright light to darkness. Night lighting of tunnels is primarily for the benefit of pedestrians and need be considered only near population centers.

The lighting system of the Broadway tunnel between Alameda and Contra Costa Counties, Calif., makes use of louver frames (see fig. 17) which gradually diffuse the light over a distance of 200 feet at the approaches of the portals. Truss frames, supported on concrete side walls, span the roadway. The trusses are spaced at approximately 34-foot centers and from their lower chords are suspended four lines of purlins consisting of 12-inch, wide-flange, 22-pound I-beams. These purlins support a series of grillages. The grillages consist of a series of vertical and oblique aluminum vanes so oriented that during no season of the year can the sun's rays pass directly through to the roadway. Openings were made through the louver panels, and lighting units have been installed.

LIGHTING INSTALLATION IN TOOTH ROCK TUNNEL DESCRIBED

The system serves the purpose very satisfactorily in the mild climate of this locality, but in a colder climate, provision to handle snow would be necessary. One

FIGURE 13.—WEST PORTAL OF THE WAWONA TUNNEL, CALIFORNIA. THE SMOOTH CONCRETE OF THE PORTAL HARMONIZES WITH THE ADJACENT ROCK FACES.

FIGURE 14.—PORTAL OF THE BIG OAK FLAT TUNNEL, CALIFORNIA. THE MASONRY PORTAL HARMONIZES WITH THE SHATTERED ROCK AROUND IT.

possible means of eliminating snow would be a shed covering with sufficient pitch for gravity snow disposal. The roof could be made as transparent as desirable by using glass panels.

The Tooth Rock tunnel in Oregon is the only rural highway tunnel in the west equipped with portal daylight illumination, and is of particular interest.[4]

The illumination within the tunnel is of sufficient intensity to provide for safe travel at normal speeds in the most adverse conditions of bright sunlight. In the past, a serious fault of highway tunnels has been the hazard to traffic created by driving from bright daylight into darkness.

Before the Tooth Rock tunnel was constructed, the Bureau of Public Roads cooperated with the State of Oregon in making comparative field tests of lighting in existing tunnels. These tests covered overhead

[4] This tunnel is described by H. D. Farmer, Senior Highway Engineer, United States Bureau of Public Roads.

FIGURE 15.—WEST PORTAL OF TOOTH ROCK HIGHWAY TUNNEL, OREGON.

Photo by the California Toll Bridge Authority.

FIGURE 16.—UPPER DECK OF THE YERBA BUENA ISLAND TUNNEL, CALIFORNIA.

incandescent and sodium lights with low-height, side-mounted fixtures with controlled beams. A system of overhead lighting was found to be more effective than side lights. The overhead lights provided a full, normal silhouette of vehicles that are passed in the tunnel, whereas the side lights illuminated the chassis only and the result was unsatisfactory for vehicles passing at normal speeds.

The installation was designed to provide a transition from bright daylight at the portals (often in summer from 10,000 to 15,000 foot-candles) to a suitable intensity of illumination within the tunnel. An intensity

of 6 foot-candles at the road surface was found to be satisfactory. The majority of the lighting units used were sodium vapor luminaires. The greater economy of operation of sodium vapor lamps as compared with incandescent lamps of equal capacity was the controlling factor in their adoption. However, near the portals, incandescent lights were used in conjunction with sodium vapor fixtures to build up a high intensity with fewer units. In this tunnel each 1,500-watt incandescent lamp produces about 33,000 lumens while the largest sodium unit produces 10,000 lumens.

There are in all 20 sodium vapor reflector luminaires of the concealed source type designed to give adequate and uniform pavement brightness and freedom from objectionable glare.

The units have the following characteristics: Straight series, type NA-9, 10,000 lumens, 31.4 volts, 6.6 amps. and 195 watts. The reflectors and units are similar to the ones originally designed for lighting traffic circles, and are manufactured from specular aluminum.

Each unit is mounted horizontally with the major axis transverse to the roadway, and 18 feet above the pavement. The close spacing of the sodium vapor lamps results in a uniform intensity of 6 foot-candles under the fixture at the roadbed. For convenience in relamping the luminaires a special design was worked out so that the units can be swung free of the concrete lining. Plug type absolute cut-outs have been provided in a flush mounted box adjacent to the sodium luminaire for disconnecting this unit from the high voltage series circuit.

All sodium luminaires are operated in a single series circuit (see fig. 18), part of which is short circuited during the hours of darkness by means of a remote-control oil switch controller. A second similar controller is provided on the primary side of the regulating outdoor transformer for deenergizing the entire circuit by means of a low-voltage switch. This controller is normally open and can close only when its operating coil is energized; this provision is for safety.

A comparison of power consumption shows that sodium vapor lamps rated at 10,000 lumens consume approximately 195 watts per hour against 526 watts per hour for similar incandescent lamps.

Nine incandescent units (see fig. 19), each consisting of seven 1,500-watt lamps and two 1,000-watt lamps furnish approximately 270,000 lumens and provide an effective transition from bright sunlight to the dimness of the tunnel. These incandescent lamp units are grouped as shown in figure 18 within a small area on the incoming traffic side of the tunnel.

Fixtures for the incandescent lights are standard reflectors mounted 16 feet above the roadway surface. The incandescent lights are connected by three-wire multiple connections in two separate circuits supplied independently by two distributor transformers located in vaults at their respective ends of the tunnel. Control is effected through remote-control, low-potential contactors.

The incandescent units with their concealed-source type of reflectors give a light of high intensity at the portals, free from glare and well distributed. While the light at all points within the tunnel is far short of daylight intensity, sufficient illumination is provided to enable traffic to traverse the tunnel safely without confusion or change in speed.

The change from a high intensity of light at the portals during daylight hours to a low intensity at night and vice versa is effected by an electric eye which operates a switch when the outside light intensity drops below or rises above 500 foot-candles. During daylight hours the lighting system is operated at full capacity except during sustained periods of dark, cloudy weather when the incandescent system may be cut out by manual controls. At night, since it is necessary only to provide lights for pedestrian traffic, no incandescent lights, and only one-third of the sodium vapor lights, are used.

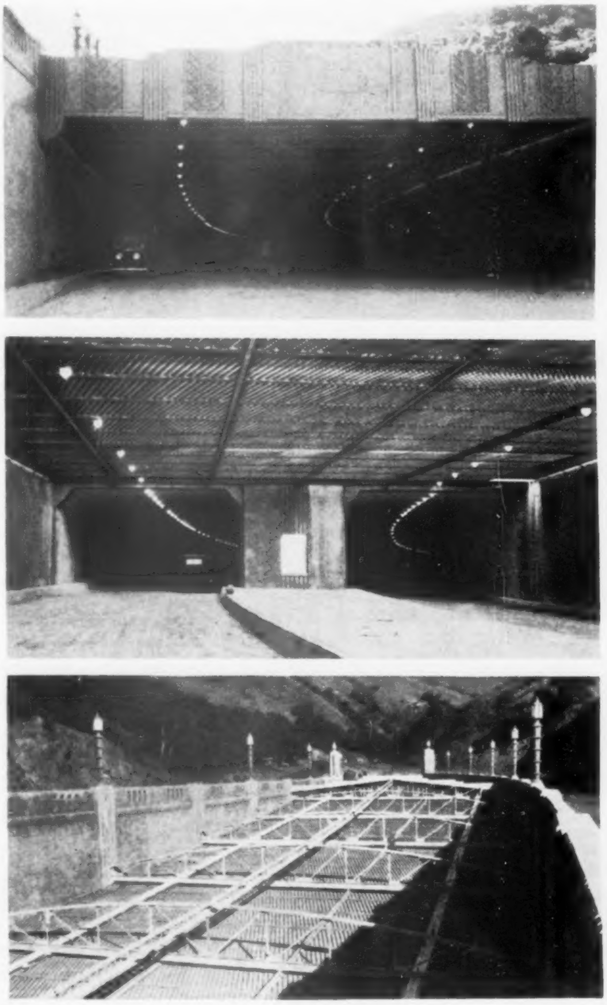

FIGURE 17.—PORTAL AND LIGHT LOUVERS OF THE BROADWAY TUNNEL, CALIFORNIA.

The photoelectric relay used is a new unit recently developed employing two phototubes instead of one, connected in parallel and mounted behind a window. This installation differs from the usual one in that the phototubes and the relay controls are located in separate boxes. The phototubes are mounted in the north wall of the vault at the west portal and the controls are located within the vault.

PLAN OF OPERATIONS IN TUNNEL CONSTRUCTION DEPENDS ON SEVERAL FACTORS

The lighting system has operated very satisfactorily, but several minor revisions would improve the design.

1. The pendant fixtures for incandescent lights near the portals do not present as good appearance as would

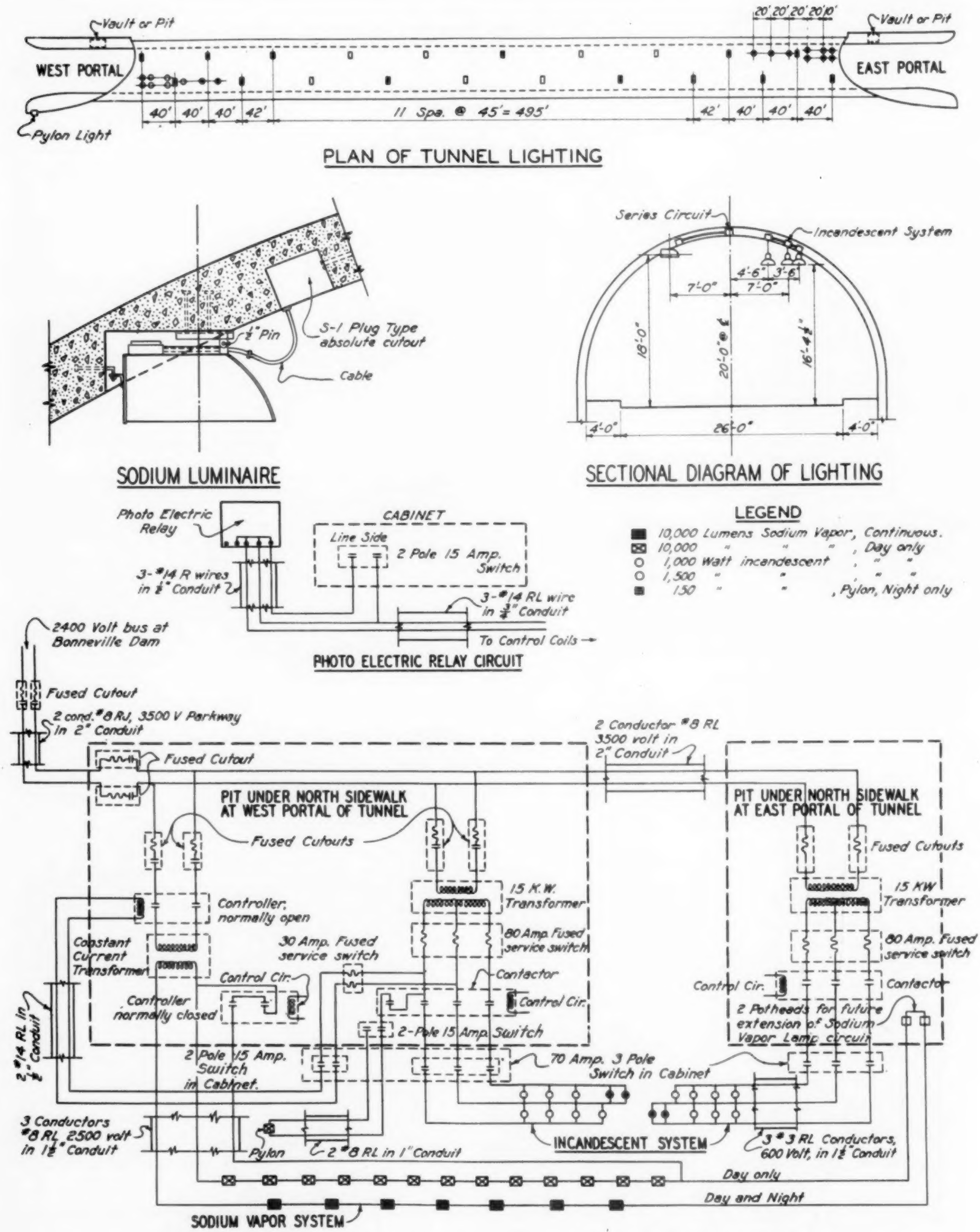

FIGURE 18.—DETAILS OF LIGHTING INSTALLATION OF TOOTH ROCK TUNNEL, OREGON.

FIGURE 19.—TOOTH ROCK TUNNEL, OREGON, SHOWING LOCATION OF INCANDESCENT LIGHT UNITS.

properly concealed fixtures countersunk into the concrete lining. A more attractive design of the sodium fixtures also could be devised.

2. Probably less intensity of light at night would be equally effective for motor traffic, adequate for pedestrians and more economical. When additional sodium lights were cut out at night, the resulting lighting was very spotty and unsatisfactory. The present lighting system is also somewhat objectionable to traffic leaving the tunnel at night, since the intensity of illumination inside the tunnel is greater than that generated by headlights outside and results in a moment of deficient vision. A system of night lights of lower intensity, but spaced closer, would be more effective. A similar result could be obtained by extending the illumination outside of the tunnel to effect a transition. This transition effect will be accomplished at the Tooth Rock tunnel when the adjacent sections of road are lighted in the near future.

3. It is believed that the transition lighting during daylight would be more effective if the first units were located 20 or 25 feet inside of the portal rather than 8 feet as in the present installation. The reflected light from the outside daylight so greatly outshines the artificial light from the first units that very little benefit is derived.

The methods and sequence of tunnel construction operations depend upon the degree to which the ground is self-supporting, free, or charged with water, and on the cross section of the tunnel.

As the East Rim Road tunnel was only 22 feet wide over-all and as the sandstone formation in general was entirely self-supporting, a pilot tunnel 9 feet wide and 8 feet high was driven on center line and at grade, followed by ring drilling.

The Wawona tunnel, 28 feet wide, was in excellent, self-supporting, granite formation. The contractor tried three methods of operation: (1) A crown heading with ring drilling and bench; (2) a narrow bench and crown heading; and (3) two successive headings and one bench. The last method was used throughout the major portion of the tunnel.

Big Oak Flat tunnel No. 3 was in the same type of rock formation as the Wawona tunnel but no headings were used and the full face was taken out. In tunnels Nos. 1 and 2 a pilot heading was used for ventilation.

The plan of operations—whether to take out the entire face or one or more headings or benches—depends upon several factors.

FIGURE 20.—GALLERY UNDER CONSTRUCTION ON THE EAST RIM ROAD TUNNEL, UTAH.

In the East Rim Road tunnel the boring could be done from several galleries (see fig. 20), but the major portion of the muck had to be taken out through the west portal. Therefore, to expedite completion, the pilot tunnel was well adapted to the purpose. The 22-foot over-all width made it possible to use a 9-foot by 8-foot pilot tunnel.

The pilot tunnel was worked simultaneously between the several galleries. When the pilot tunnel was completed between the west portal and the first gallery, full-bore operations were started because ring drilling, loading, and shooting could proceed at the same time as mucking. The pilot tunnel to a large extent solved the ventilation problem. The natural draft through the pilot tunnel was augmented by the exhaust from the shovel which was powered with compressed air, and no difficulty was experienced in using gasoline motor trucks as hauling equipment. In the Maricopa-Ventura tunnels and the Big Oak Flat tunnels Nos. 1 and 2, pilot tunnels were used for ventilation, but were not ring drilled. These tunnels were of short lengths and this method was used so that special ventilation machinery would not be needed.

The cross section of the pilot drift must be ample to allow easy handling of the long steel drills for subsequent ring drilling. The drill holes should extend at least a foot beyond the neat line of the section at the extreme points if the entire section is to be taken out in the two operations, that is, the pilot tunneling followed by ring drilling, loading, and blasting.

The placing of concrete lining in highway tunnels, in the past, has presented difficult problems.[5] Severely restricted working conditions and the necessity that the concrete reasonably fill all voids resulting from

[5] The following discussion of concrete lining in highway tunnels is by G. W. Mayo, Senior Highway Bridge Engineer, United States Bureau of Public Roads.

overbreak and areas between timber sets that must be left in place, etc., have dictated the use of extremely wet mixtures. Honeycombed areas and a rather pervious concrete have been the natural results.

The tunnel cross section generally permits the use of forms in the shape of a full-centered arch of comparatively short span. Structural requirements to carry the superimposed loads would permit a thin arch section but practical considerations in placing concrete generally require a somewhat thicker lining.

In recent years there has been developed a pump of the plunger type that is capable of handling dry, harsh mixtures of concrete. The use of this pump, together with vibrators both of the internal and external type, make possible the placing of tunnel lining equal in quality to concrete placed under ordinary conditions. Such equipment was used with excellent results on the following tunnels: Broadway, Yerba Buena, and Waldo, in California; Tooth Rock, in Oregon; and East Rim Road, in Utah. Tests of the 28-day strength of concrete placed in the Broadway tunnel showed that it averaged well above 3,000 pounds per square inch in compression.

PLACING PNEUMATICALLY APPLIED MORTAR REQUIRES SPECIAL CARE

Concrete pumping equipment is available in either mobile or stationary units. It has performed satisfactorily using up to the equivalent of 1,000 feet of pipe where no lift was involved. On tunnel work it ordinarily discharges directly into the forms, obviating the use of chutes or other distribution devices and consequently eliminating segregation of the aggregate from the mortar. The forms must be set in comparatively short sections and must be of substantial construction to permit the efficient use of internal vibrators and to withstand the pressures developed in pumping.

Where heavy underground pressures develop, or where the material through which the tunnel is being driven slakes rapidly in air, it is essential that the lining be kept comparatively close to the excavation heading. Experience has indicated that even though a fully lined tunnel is not contemplated, the section should be so designed as to permit the placing of lining without interference from timber sets which may need to be left in place. Costly changes in plans will thus be avoided.

Where pneumatically placed mortar lining has been placed in tunnels after the bore is complete, certain precautions are necessary to insure satisfactory results. The most important precaution is the control of air currents and temperatures during operations. In the Wawona tunnel such control was accomplished by hanging a heavy canvas curtain.

Adequate lighting is also of importance, since uniformity of application is only possible when the nozzle man is a skilled operator and all unnecessary shadows are eliminated. This lighting was much more of a problem on the Wawona than on the East Rim Road tunnel, since in the latter the surface broke smoothly while the surface of the Wawona tunnel was decidedly rough.

It is important that the rock surfaces be clean and free from dust and encrustations. The Wawona tunnel surface was washed with a stream of water under a nozzle pressure of 70 pounds per square inch. Washing was done at least half an hour before mortar was applied.

The amount of pneumatically placed mortar overran the estimated quantity in the Wawona tunnel for 3 reasons, as follows:

1. Bulking of the sand. The specifications limited the moisture content of the sand between 4 percent and 8 percent but the mix was designed on the basis of dry sand.
2. The excessive amount of rebound material obtained because of the very irregular rock surface. This rebound resulted in more sacks of cement being used per cubic yard in place than had been anticipated.
3. The actual surface area covered was considerably in excess of the area estimated, because of irregularities.

During construction of the Wawona tunnel several important features were observed in the operation of the pneumatic equipment.[6]

The cement gun was not equipped with an air gage or velocity meter, so some difficulty was experienced in maintaining a constant air pressure at the gun. The gage was located on the compressor about 40 feet from the gun. The air pressure was fairly constant at 45 pounds per square inch but frequent fluctuations were observed, caused by clogging of the material at the gun outlet or throughout the length of hose. These fluctuations caused variations in the rate of discharge of the mortar, resulting in poor hydration at the nozzle and a consequent greater loss of material by rebound. The fundamental cause of the material clogging was high surface moisture content of the sand which varied between 6 percent and 8 percent at the time observation was made. When the surface moisture content dropped below 6 percent no further trouble was experienced.

Indications are that for efficient operation the surface moisture content of the sand should be between 3 percent and 6 percent. Material containing less than 2.5 percent moisture will discharge too quickly through the gun and will not receive sufficient water for proper hydration.

It was found impractical to operate with more than 150 feet of hose. Greater length caused stoppage and resulted in considerable delay even though the air pressure was proportionately increased. When using over 100 feet of hose the contractor used a 1-inch nozzle and when using less hose a 1½-inch diameter nozzle was used. The use of the larger nozzle resulted in a better grade of pneumatically applied mortar with considerably less rebound.

The material was batched and mixed continuously. To avoid any possible chance of hydration of the cement before it was shot through the gun, the mixing box and gun were emptied and cleaned every hour.

As has been stated, considerable material was lost because of rebound. There seems to be no particular reason for wasting this material except where linings of high strength are desired. If precautions are taken to prevent water from coming in contact with the rebound material there is no reason why it should not be used again, if collected promptly. The strength of the resulting mortar might be affected by this reuse but the saving in material cost would justify a somewhat decreased working stress. This reuse would apply to any project where pneumatically applied mortar was employed exclusively for protective purposes.

It was found highly important for the rock surfaces to be clean and free from dust before applying mortar

[6] Further operations in the Wawona tunnel are described by E. B. Payne, Junior Highway Engineer, United States Bureau of Public Roads.

FIGURE 21.—A SECTION OF THE WAWONA TUNNEL, CALIFORNIA, SHOWING THE FORMS AND COLLAPSIBLE CENTERING USED IN PLACING CONCRETE LINING.

to them. In some instances the material sagged because of insufficient bond and at times dropped completely away from the rock. In such cases the spots were given another application of mortar.

CONSTRUCTION OF PERMANENT LINING IN HEAVY GROUND DIFFICULT

A thickness of ¾ inch is apparently the maximum that can be easily applied directly overhead when using ordinary portland cement. If a greater thickness is desired in one coat, 3 percent to 5 percent of calcium chloride should be added to the dry mixture or should be placed in the mixing water.

If the cover is generally self-supporting, lining a tunnel is a simple operation; but where heavy ground is encountered and temporary timbering is necessary, unusual care must be exercised in selecting means of supporting the lining. In the North Pacific Forest Highway tunnel in Idaho, the cover was so heavy that the timber supports were pushed into the lining section to such an extent that the original plan of concreting the timber supports in place had to be abandoned. It was necessary to place reinforced concrete rings between the sets, and later remove the sets and fill in the spaces between the rings with reinforced concrete. Note the overstressed timber posts and square sets in figure 6. Also note the reinforcing steel in place preparatory to concreting between the rings (fig. 7).

Where the cover is generally self-supporting, collapsible forms can be used, allowing easy movement as the concreting progresses. Figure 21 shows movable forms used in the Wawona tunnel. The carrier with lifting jacks in place on the raising platform is shown, also the strutting used during the placing of the concrete.[7]

The tunnel required concrete lining for 590 feet next to the upper portal. The thickness of lining was 18 inches at the springing line and 12 inches at the crown. The concrete was reinforced with ¾-inch square bars on 12-inch centers both transversely and longitudinally.

Bureau regulations against excessive drop and running of concrete in the forms led to the adoption of a rather elaborate placing system. Wooden forms, constructed in 10-foot sections and so built that they could be collapsed for moving to adjacent sections, were used. Additional centering, required while pouring, could be removed after 2 days. The forms were left in place for 5 days.

Aggregates were transported in wheelbarrows to the mixer which discharged directly into the placing gun. The discharge pipe from the gun was carried over the top of the forms, terminating in steel chutes which were carried down the sides of the forms to within 5 feet of the bottom. These chutes were in sections which were removed as the concrete built up. The entire placing installation was carried on wheels on a central track and was moved up and down the track by means of a hoist.

Thirty feet of lining were poured every 2 days, using the intervening day to move the forms and bring in materials. By moving the entire installation, the discharge boxes could be moved back and forth over the 30 feet that was being poured, thus depositing the concrete directly into final position. Tamping of the concrete was possible in all but the crown of the arch. In addition, air vibrators were used on the face of the forms.

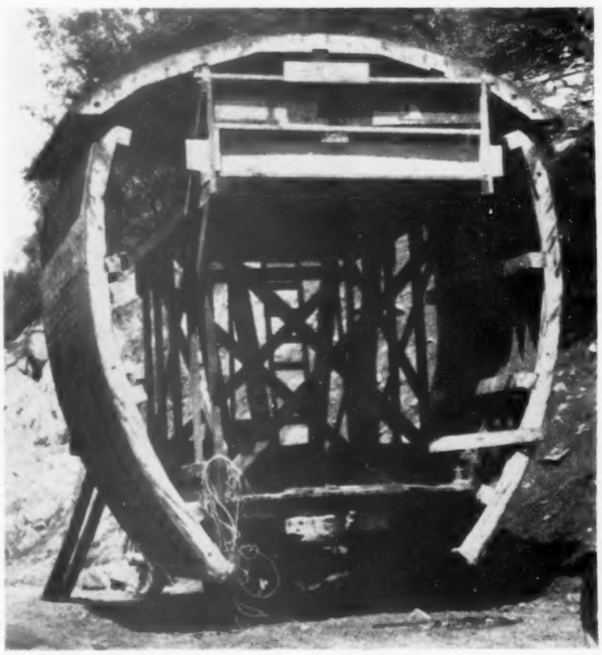

FIGURE 22.—COLLAPSIBLE STEEL FORM USED IN LINING THE BIG OAK FLAT TUNNEL.

DATA GIVEN ON CONSTRUCTION OF EAST RIM ROAD TUNNEL

At one place there was a rock fall of about 105 cubic yards from the top of the tunnel. The highest point of this pocket was 17 feet above the top of the tunnel. Through the section affected by this fall, the concrete lining was thickened to 18 inches all around the arch (see fig. 9). Three vertical pipes, extending to the top of the hole, were placed through the lining before pouring. After the concrete lining had cured a sufficient time, the entire hole was pumped full of wet sand to support the rest of the rock and form a cushion above the concrete lining.

On the Big Oak Flat tunnel, improvement was made in centering the lining by using steel shapes, and the collapsible lining was hinged in two places, as shown in figure 22.

[7] The use of these forms and the placing of concrete are discussed by T. M. Roach, Associate Highway Engineer, United States Bureau of Public Roads.

From the East Rim Road tunnel, 5,613 feet long including the length of the six galleries, approximately 72,000 cubic yards of muck were removed.[8] Two hundred ninety-two thousand pounds of 40 percent powder were required, or an average of 4 pounds to the cubic yard.

The general operations consisted, as previously mentioned, of constructing a pilot tunnel on center line and grade (see fig. 5). Where poor cover was encountered, the location of the pilot tunnel was changed to a top heading of the same cross section along the center line.

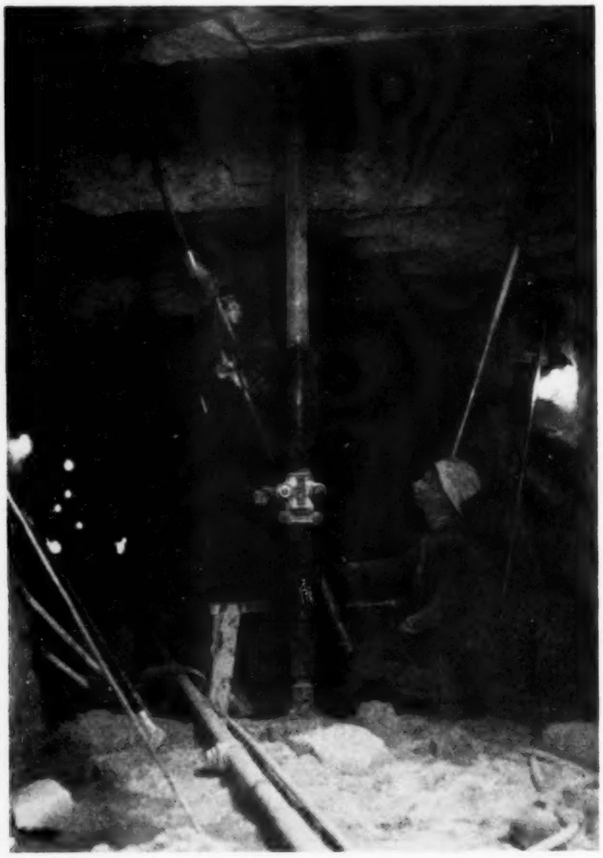

FIGURE 23.—COLUMN USED IN RING DRILLING, AND STOPER DRILL BEING OPERATED IN THE CONSTRUCTION OF THE EAST RIM ROAD TUNNEL.

A central compressor plant with extensive pipe system permitted operations at several galleries or pilot tunnel headings at the same time. The points of attack from the galleries and progress are shown in table 2.

The numerous crews engaged worked a total of 1,275 8-hour shifts in 273 calendar days. The average footing made each 8-hour shift was 4.4 feet, or 20.6 feet per calendar day by the combined shifts. The section of the pilot tunnel involved a quantity of 2⅔ cubic yards per foot of length.

The drilling in the side galleries and the pilot tunnel was carried on with jackhammers, column drills, or liners. All blasting was done using fuse. Muck was loaded by hand into mine cars, except where muckers could be taken into the headings.

All drilling of the material between limits of the pilot bore and the perimeter of the main bore, except where timbering was necessary, was done by ring drilling. (See fig. 23.) Stoper drills were set on vertical columns on the center line of the main tunnel, and anchored between the roof and the floor of pilot tunnel. Stopers were thus set at points 4 feet above designated grade and radial holes were drilled around the pilot tunnel for the full tunnel section above the floor. These holes were drilled to the perimeter of the theoretical bore (see fig. 5 for details) and the rings of holes were spaced at 3-foot intervals. In blasting the material in the main bore, 12 rings of holes were shot at the same time.

[8] Construction methods used in the East Rim Road tunnel in Zion National Park are described by R. A. Brown, Associate Highway Engineer, United States Bureau of Public Roads.

FIGURE 24.—TIMBERING BEING CARRIED FORWARD AS EXCAVATION PROGRESSED IN THE EAST RIM ROAD TUNNEL.

TABLE 2.—*Progress in the construction of the East Rim Road tunnel*

Gallery station	Direction	Working time	Length	Rate per day
		Days	*Feet*	*Feet*
71+82	West	50	527	10.5
71+82	East	22	214	9.7
69+50	do	22	292	13.27
62+48	do	48	569	11.85
49+48	West	54	731	[1] 13.53
49+48	East	57	655	11.5
37+52	West	40	543	[1] 13.57
37+52	East	53	797	[1] 15.0
29+55	do	43	882	[1] 20.5

[1] Crews on bonus.

Before awarding the contract for construction of the tunnel it was thought that the ground throughout the greater part of the tunnel would be stable enough so that only a very small amount of lining would be required. When heavy ground was encountered in the pilot tunnel, however, the pilot tunnel was discontinued on grade and a top heading on springing line grade was driven and timber lining was placed between the springing line and the roof of the main tunnel. The bench below the top heading was left in place until the power shovel was ready to excavate it. This bench then was breast drilled and shot and the shovel mucked it out. As the muck was removed, posts to support the timber lining were placed under the wall plates. (See fig. 24.) The equipment used was as follows:

- 6 jackhammers.
- 12 liners and stopers.
- 2 150-horsepower motors.
- 2 stationary compressors, capacity 850 cubic feet per minute each.
- 1 air (tunnel type) shovel, ½ cubic yard.
- 5 trucks—3 to 5 cubic yards capacity.

1 32-inch fan.
2 mucking machines.
7 mine cars.
4 hoists.
2 portable compressors.
1 automatic drill sharpener.
4 steam pumps.
Miscellaneous track, pipe, electrical equipment, and small tools.

TIMBER LINING REPLACED WITH STEEL AND CONCRETE LINING

Five years after completion of the East Rim Road tunnel it became evident that the timber lining in several sections was in distress and that it was necessary to place some permanent type of lining. In the most hazardous sections, structural steel and concrete were used as follows.[9]

The failure of the timber lining was evidenced by shifting and split arch caps and segments, deformed and crushed wall plates, and tipped posts. Sufficient timber lining was removed to make room for one 10-inch steel **I**-beam. (See fig. 1.) An **I**-beam ring was then installed, after which the sandstone outside of the beam was stulled and blocked and sufficient additional lining was removed to install another beam. Thus the operation was carried on until the entire timber section was replaced with the **I**-beams thoroughly wedged and the seamy, blocky, and loose sandstone above blocked and stulled in place.

After each section was completely supported with the steel **I**-beams, forms were placed on the inner face only and concrete was pumped between the **I**-beams and in contact with the rock, except that the larger voids were filled with old timber, rock, or sand to form a cushion. The concrete was placed by a pump of the plunger type.

Because of the narrow spaces of 10-inch minimum thickness in this special lining of welded **I**-beam sets, it was necessary to use concrete having a 5-inch slump to eliminate the possibility of leaving voids between the **I**-beams. The concrete was efficiently placed by skilled crews. The 10-inch steel **I**-beams came in three sections—two steel wall posts and an arch of steel—and were welded together to form one supporting ring. The sections were butt welded with a minimum $\frac{3}{16}$-inch bead completely around the joint except on the inaccessible back face.

The joints were at the springing lines and the steel ribs thus formed were placed as the sections of failing timber were removed. The steel posts were set to line and grade; the steel arch member was placed and the joints welded; and then concrete pedestals were poured at the bases of the posts. After the concrete had set sufficiently, using extra cement for early setting, the loose, blocky, and heavy ground over the arch and at the sides was blocked, wedged, and stulled to make a tight back and rigid support before filling the spaces between the **I**-beams with concrete. At several points it was necessary to place stulls from the tunnel floor to support the load until the **I**-beam could be erected and welded, and the pedestal concrete had set sufficiently.

Several old rings of 12- by 12-inch timber were found as much as 2 feet too low and were supporting heavy ground that was at many points also too low. It was necessary to cut back to obtain sufficient clearance to place the **I**-beam. Though the work was extremely hazardous, no one was injured. Experienced tunnel men, steel workers, and carpenters performed the work. The installation of the **I**-beams proved an ingenious method of repair for these sections where the timber had failed, because without steel **I**-beams or some temporary support, the placing of concrete lining in these sections would have been very slow and extremely dangerous. The repair work would probably have cost considerably more by other methods.

Several methods can be used in excavating tunnels. The contractor should select that method best adapted to the particular project, considering the nature of the formation, the size of tunnel cross section, and disposal of the material. The various systems of drilling used in several western tunnels are illustrated in figures 5 and 25. A detail discussion of the methods used in boring the tunnels in Yosemite National Park follows.[10]

Some of the factors which influence the choice of a method of driving a tunnel should first be considered. When driving tunnels of the size required for highways, most contractors prefer to carry a heading (this term is used here to describe a drift along the direction of the bore of such size as to permit one or more miners to excavate material within the cross section of the tunnel) some distance in advance of the excavation of the full tunnel section for the following reasons:

1. The heading discloses the character of the ground prior to opening the full tunnel section.
2. The heading offers access to points from which the crown can be reached and timbering started if required.
3. Short drill columns and drill bars can be used in the heading, thus eliminating the necessity for a large drilling setup and high working platforms.
4. Short blasting rounds are usually used in advancing a heading, and the loss is comparatively small if the blast fails to break to the full depth of the drill holes.
5. In hard rock, the blasting of the bulk of the tunnel section is more effective if there is a hole, such as a heading, toward which the material can break.

Other factors influencing the choice of methods are time allowed, equipment on hand, shape of tunnel section, etc.

CONSTRUCTION OF WAWONA TUNNEL DESCRIBED IN DETAIL

The tunnel section used in the Wawona tunnel is a semicircle, 14 to 15½ feet in radius, on a 6-foot springing line. The effective width of a top heading in such a section is reduced, as the top of the arch drops rapidly beyond 5 or 6 feet each side of the center, and interferes with the proper pointing of the drill holes. Lowering the heading from the crown of the tunnel would destroy its effectiveness as a starting point for timbering, and result in blocking of the end of the heading by the muck pile if long bench rounds had been blasted.

Three drilling systems were used by the contractor in the Wawona tunnel, and it will be noted that each system involved the use of some form of heading. (See fig. 25.)

The first method was used for the first 335 feet. Under this system, the crown heading (10 feet by 11 feet) was advanced as fast as possible. Back of the heading, but well ahead of the bench, four drilling machines, swung on cross arms from a horizontal bar, drilled holes in parallel rings 3 feet apart to break out the remaining portion of the heading to the level of the

[9] This work is described by F. L. Davis, Assistant Highway Engineer, United States Bureau of Public Roads.

[10] This discussion is by T. M. Roach, Associate Highway Engineer, United States Bureau of Public Roads.

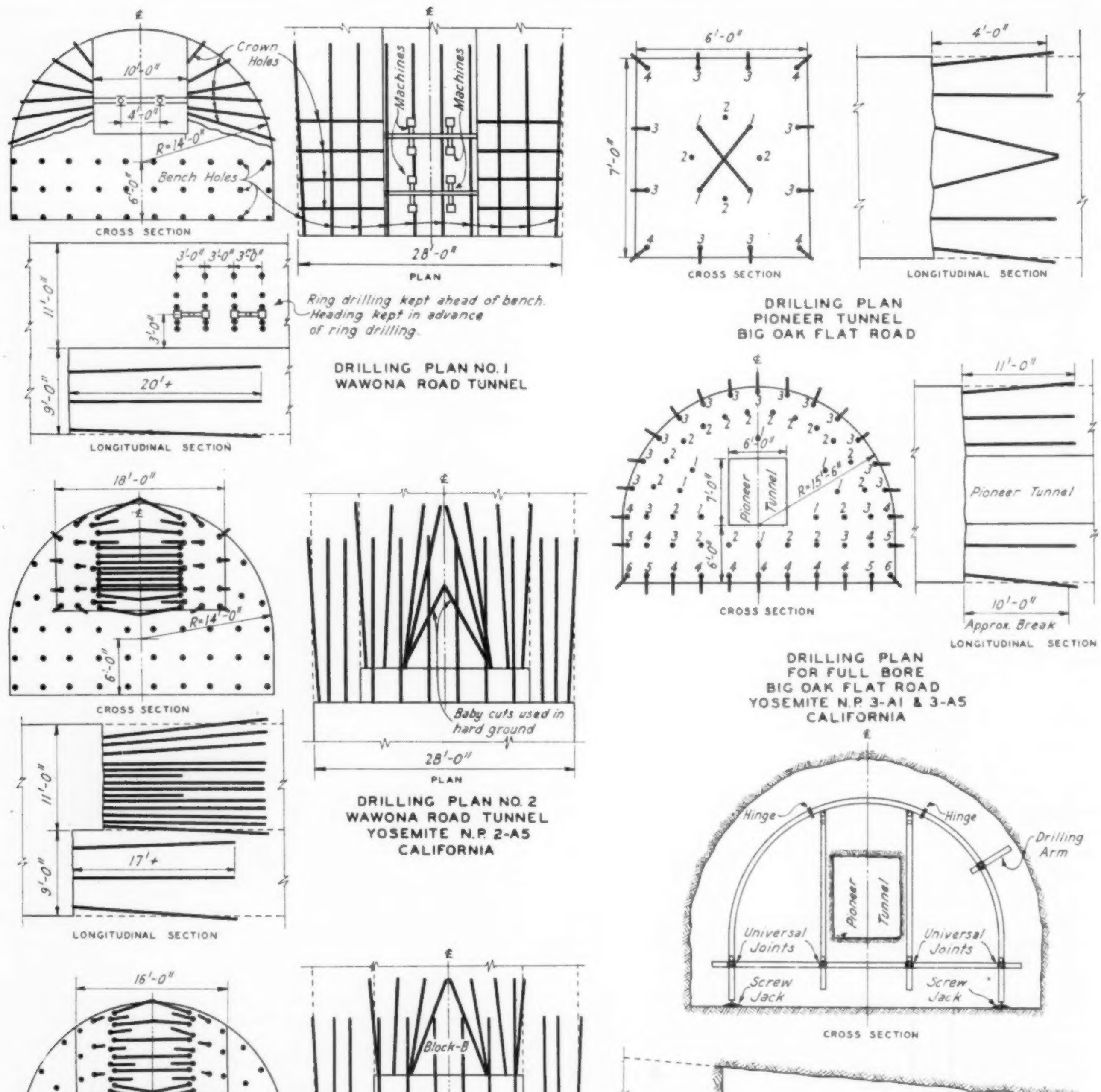

FIGURE 25.—DRILLING PLANS FOLLOWED IN THE CONSTRUCTION OF WESTERN HIGHWAY TUNNELS; ALSO DRILLING JUMBO MOUNTED ON TRUCK.

bench. Bench holes were drilled from a cross-bar set-up, practically paralleling the tunnel center line.

In blasting, the bench hole shots were fired in conjunction with 6 or 7 rings of top holes. Delay detonators were used to assure the ring shots exploding before the bench shots, and to give proper firing order for the holes in the bench. Heading rounds were fired at the same time as the bench rounds if they could be prepared in time. The heading was mucked by hand, the muck being dumped over the bench and re-handled by the mucking rig which was used to handle the bulk of the blasted material.

It was found that the heading could not be advanced nearly so fast as the bench could be broken; that it was very difficult to keep air pipes in place past the mucking rig to feed the machines drilling in the heading; and that there was, in the heading, constant interference with the machines drilling the ring holes ahead of the bench. The daily average advance of the entire section was only 5.6 feet, and this system was abandoned in favor of the second method.

The second drilling plan utilized a heading 18 feet wide, kept only a short distance ahead of the full tunnel face. A set-up for machines drilling from short arms swung from a column was used in the heading. The drill holes varied from 13 feet to 19 feet in depth, but usually gave about a 17-foot break.

In erecting the drilling set-up for the bench, two horizontal bars were placed across the tunnel, the first 1 foot above grade, and the second at the springing line. These bars were tightly jacked against the rock sidewalls. Clamped to these bars was a curved bar, 18 inches from the sidewall and parallel to the curve of the tunnel section, extending up into the section of tunnel beside the heading. This bar was used as a guide in drilling the area above the bench and was shifted from one side of the tunnel to the other as drilling progressed. Machine clamps could be placed on any part of the curved or horizontal bars. The drill holes were spaced as shown in figure 25 and were drilled approximately parallel to the tunnel center line to a depth of 13 to 19 feet. Heading and bench were blasted together, delay detonators being used to give the proper sequence of explosions. Charges in all holes in the heading exploded before charges in the holes in the bench.

Under the second method the maximum daily advance was 17 feet, while the average was only 13 feet. It was very difficult to remove the muck from the heading after shooting using the long holes, as they sometimes produced "bootlegging", or failure to break to the full depth of the holes. This loss sometimes ran as high as 4 or 5 feet and necessitated reshooting with consequent loss of time. Widening the heading to permit longer rounds would merely have lowered the heading sidewall height to a point where it would have been impossible to place the holes properly, and lowering the heading from the crown would have resulted in partial blocking of the heading by the muck pile and failure of the muck from the heading to blast clear of the bench.

The contractor was equipped and staffed for working 24 hours per day, doing most of the drilling and blasting in one shift and the mucking in the two remaining shifts. The mucking operations had been developed to the point where the contractor was convinced that a full 20-foot round could be cleaned out during the two mucking shifts, and he accordingly changed to the third method, which he believed would produce the desired footage.

Under this system of drilling, the contractor endeavored to shoot and remove two 10-foot rounds in the heading and one 20-foot round in the bench each 24 hours. One of the heading rounds was drilled and fired in conjunction with the bench round, the second heading round being drilled and fired during the first mucking shift. The arrangement of drill holes and firing order were essentially the same as was used in the second method.

Using the third system it was necessary to blast twice each day, each blast resulting in a loss of at least 1 hour while the smoke and gases were being cleared out. Further delay was caused by extra moving of the shovel for cleaning up the muck after each blast. It was found impossible to complete the working cycle in 24 hours, and all shifts were accordingly worked on call, their hours changing each day, with consequent disorganization.

The third drilling system was used in driving the last 3,157 feet of the tunnel. The daily average advance was 13.6 feet, although the advance per blast was 20 feet or more, as had been estimated.

The costs using the second and third drilling methods were practically the same. It will be noted that the average advance was only 0.6 foot per day more under the third plan. It is believed the costs would have been lowered slightly if the contractor had not changed to the third system but had continued the second system and had concentrated on lowering the costs by increased efficiency.

All mucking was done with a ¾-swing power shovel, mounted on crawler-type tracks and operated with compressed air. This rig was slow and cumbersome, and production was low. It was usually 3 hours after the mucking shift started before the first train of material came out of the tunnel. Operating costs were high, as the shovel would not operate on the output of one compressor of 1,250 cubic-feet-per-minute capacity, and it was necessary to run two compressors requiring 400 horsepower. The same size shovel of the conventional type will operate on one 75 to 100 horsepower motor.

Material was hauled from the tunnel in side-dump cars, operated on tracks by combination battery and trolley locomotives. In addition to the high cost of installation and maintenance of this haulage system, the equipment did not operate well on the 5-percent grade of the tunnel. The locomotives could barely push 3 empty cars up the grade, and a great deal of trouble was encountered in controlling the loaded train while coasting down grade.

It appeared that operations involving the blasting and mucking of the full face, with approximately the same daily advance or possibly less, would have been more economical.

DRIVING OF BIG OAK FLAT TUNNELS DISCUSSED

The following factors were considered when deciding upon the method to be used in driving the two short tunnels on the lower portion of the Big Oak Flat road.

1. The two tunnels totaled only 540 feet in length, so any expensive equipment set-up would have materially affected the cost.

2. The available compressor could supply air to operate only about 7 small drilling machines or four large drilling machines. Two machines that could be made over into small drifters were on hand.

3. No bad ground was anticipated, and no top heading was believed necessary. It was believed, however, that a pioneer bore should be used to provide for ventilation while enlarging to full size and to give a better break to the material while driving the full tunnel section.

4. The power shovel on hand was considered capable of mucking out only about 10 feet per day, so long rounds were out of the question.

5. All drill steel on the project was of the 1-inch hexagonal type, threaded for detachable bits. This steel could be used with small drifters, but was unsuitable for use with large machines. Use of this steel and the bits made purchasing of drill sharpeners and furnaces unnecessary.

6. The time involved in driving a pioneer bore through the tunnels would not delay completion of the project, as the pioneer bore could be driven through the first tunnel before the shovel was available to start the enlarging work. The pioneer bore through the second tunnel could be driven while the shovel was working in the section between the tunnels.

It was accordingly decided that a pioneer bore, 7 feet by 6 feet should be driven through both tunnels and that the enlarging work would be done at the approximate rate of 10 feet per day. The drilling was to be done from a frame, or "jumbo", all holes being drilled approximately parallel to the center line of the tunnel. The pioneer bore was located with its lower edge on the springing line of the tunnel section. The pioneer bores were drilled as shown in figure 25; the resulting advance was between 3.5 feet and 4 feet per blast. Two shifts were used on this work each day, and the daily advance varied between 7 and 8 feet. All mucking in the pioneer bore was done by hand, and the material was transported in a small car, hand operated on tracks. All blasting was done with electric detonators and the firing order was controlled with delays, as illustrated by the numbers on figure 25.

The drilling jumbo was mounted on a flat-rack truck, and was moved in and out of the tunnel for each drilling shift. This jumbo is illustrated in figure 25 and is made of extra heavy 4½ inch pipe, curved to follow the neat lines of the tunnel arc but having a radius 3½ feet less than that of the tunnel. The uprights and braces are fastened to the truck, while the curved side arms are hinged near the top to permit swinging them out of the way while moving the jumbo. A solid bar, 25 feet long was placed across the tunnel and solidly clamped to the curved arms, 3.5 feet above the tunnel grade, while drilling was in progress. Jack screws on the bottom of the curved arms served to lift some of the weight from the truck and to brace the entire frame solidly. Drill arms could be swung out from any part of the frame, or the machines could be mounted on any portion of the frames or braces.

Drill holes were required on approximately 3-foot centers, and were drilled by using drilling arms 4 feet long clamped to the frame with universal clamps. The truck was placed on center line and the frame jacked to grade. Six drilling machines were mounted on the frame at one time, and drilling was started at the top of the frame. The machines were moved down the frame as drilling progressed. The pointing of each drill hole was checked by the shift boss. Approximately 60 holes were required to break out each section. These holes were drilled in two shifts, the first shift setting up and starting the drilling, while the second shift completed the round and loaded and blasted the holes. The mucking was done in one shift, all material being transported in trucks.

This system was very successful in the two short tunnels, and is believed to be definitely superior to the system used in the Wawona tunnel. Powder consumption was very low, the pioneer bore requiring 14 pounds of powder per cubic yard while the enlargement required only 2.4 pounds per cubic yard. The average was 3.3 pounds per cubic yard as against about 7 pounds per cubic yard in the Wawona tunnel and an estimated 4.6 pounds per cubic yard in the 2,167-foot tunnel on the Big Oak Flat road.

Of even more importance than the cost was the effect this system had on the final shape of the completed tunnel. The material encountered was badly seamed, and considerable overbreak was unavoidable. Under this method the heavy blasting required close to the crown when a top heading is used was avoided, and only light shooting to break out the small amount of material from above the top of the pioneer bore was required. None of the rock above the crown was shattered, all overbreak being the result of material breaking away from well defined seams above the neat lines.

In driving the 2,167-foot tunnel on the Big Oak Flat road, it was decided that the drilling jumbo developed for the two short tunnels would be used, but that it would be modified to provide for platforms swinging from the main jumbo for work on the sides. This eliminated the second truck with platforms which had been used on the short tunnels.

LOADED TRUCKS PULLED OUT OF TUNNEL BY ELECTRIC HOIST

Because of restrictions on the location at which the spoil could be dumped, the Big Oak Flat tunnel was driven down grade. On down grades electric haulage, besides involving a large capital investment and installation cost, is generally not efficient and involves transfer of the material to trucks for the further haul outside of the tunnel. It was therefore decided that trucks would be used in this tunnel, avoiding the necessity of using the truck engine inside the tunnel by coasting the trucks in and pulling them out. The use of trucks, which were backed into the tunnel for loading, necessitated the use of a full revolving shovel for mucking.

The use of a pioneer bore was not practical because of the time required to put such a bore through and because electric haulage would be required. The drilling system illustrated in figure 5 was therefore adopted. It is a full face system using about 100 holes, with the cut holes, which are loaded the heaviest, kept well away from the crown of the tunnel.

A compressor set-up involving approximately 1,250 cubic feet of air per minute was required to handle the drilling and shop work. Six drills are used, each machine being of the automatic-feed, drifter type.

The drilling and blasting were done in two shifts, each shift using the six drills. Holes were drilled as shown in figure 5, the pointing of the hole and the proper distribution of electric delay detonators being checked by the shift bosses. All blasting was done by electricity, the firing switch being outside the tunnel. It was usually possible to blast about 2 hours before the mucking shift was started, thus giving ample time for ventilation of the tunnel.

Ventilation was provided by a blower with a 24-inch ventilation pipe, supplemented by a portable blower and a 12-inch flexible air pipe near the working face.

Mucking was done in one shift by a full revolving $1\frac{1}{4}$-cubic yard shovel powered with an electric motor. Power was supplied to this shovel through a special three-conductor drag cable, so constructed as to resist the abrasive and cutting action of the rock bottom.

Hauling was done with 5-cubic yard dump trucks. A double drum electric hoist was mounted outside of the tunnel portal, the cable between the two drums being endless and going over rollers on the tunnel floor and around a tail block which was kept about 40 feet from the working face. Hoisting could thus be done with either drum, and hoisting of a truck could be started as soon as the preceding truck was outside the tunnel. Each truck was equipped with a 60-foot choker cable. Trucks were coasted into the tunnel backwards, and were connected to the hoisting line, when loaded, by means of a special choker hook. After clearing the tunnel portal, the trucks were driven under their own power to the dump, which was about 1 mile from the portal.

Under this system approximately 10 feet to 12 feet were advanced per cycle, involving the full 24 hours. It is believed that the same system could be used to give a daily advance of from 18 feet to 20 feet if sufficient transmission line, transformers, compressors, and drills were used so that larger rounds could be drilled and blasted in 8 hours and the mucking carried on in two shifts, but this system would involve more than doubling the amount of equipment.

The only apparent disadvantage of this system is that if bad ground is encountered the full face is open, and timbering is very difficult. Nothing but full timber sets can be placed, and these cannot be blocked in the center of the tunnel or it is impossible to take the large equipment through. On a short stretch of heavy ground encountered in the Big Oak Flat tunnel, in order to avoid blocking the roadway to movement of equipment, the timbering was reinforced with concrete between the sets for the full depth. This concrete was built up with mortar by the pneumatic gun placement method. This heavy ground also necessitated the use of a heading. Mucking was done by hand for a short portion of the section.

The ventilation system of the Wawona tunnel is of particular interest and will be discussed in some detail.[11]

Carbon-monoxide gas is a serious menace in the operation of automobiles in tunnels. The pure gas is odorless, tasteless, and invisible. Its very toxic effect does not, however, produce a warning symptom. An ingenious ventilation system was installed in the Wawona tunnel in Yosemite Park to keep the tunnel free from too great a concentration of this dangerous gas.

Meteorological data indicated that natural draft could not be relied upon entirely as it was extremely variable. Calculations showed that carbon-monoxide gas could accumulate to dangerous concentrations during periods of heavy traffic. It was decided, therefore, to install an automatically controlled ventilation system. Natural draft was used as much as possible and was supplemented by the ventilating fans when needed to keep the carbon-monoxide concentration within safe limits.

Three horizontal adits or smaller tunnels at right angles to the main tunnel were driven to the face of a cliff to assist the natural draft. Two of these adits are 7 feet by 6 feet and 300 feet long. They are located at the quarter points or about 1,000 feet from their respective portals. The third or main adit is of the same cross section area as the tunnel and is 500 feet in length. It is centrally located, and in it are installed three 9-foot fans with a combined air delivery of 300,000 cubic feet per minute. (See fig. 26.)

[11] This discussion is by Walter Champion, Senior Engineering Aide, United States Bureau of Public Roads.

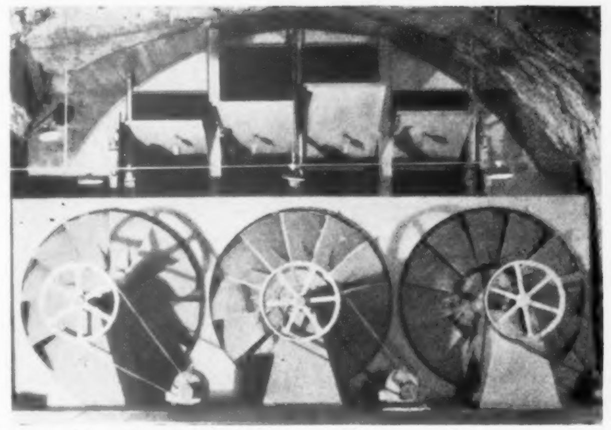

FIGURE 26.—EXHAUST AIR FANS USED IN VENTILATING THE WAWONA TUNNEL.

CHEMICAL ANALYZERS DETERMINED CARBON MONOXIDE CONTENT OF TUNNEL AIR

Each fan has 12 blades, and is of the auto vane, ball bearing, pedestal-mount type. The capacity of each fan at full speed (400 revolutions per minute) is 100,000 cubic feet per minute. At half speed, or 200 revolutions per minute, the capacity is 50,000 cubic feet per minute. The fans are connected by means of a belt to two-speed induction motors of 25 and 12.5 horsepower when operating at 1,800 and 900 revolutions per minute, respectively.

The concentration of carbon monoxide in the tunnel is determined by two chemical analyzers. Samples for each analyzer are taken through a 1-inch intake pipe, one pipe taking a sample of air in the eastern half of the tunnel and the other a sample of air in the western half. Each analyzer is equipped with a rotary air pump and draws continuous samples of air through its intake pipe. The air sample is thoroughly cleansed of all dust impurities and accurately regulated to predetermined volume before entering a hopcalite cell for the determination of its carbon-monoxide content. The concentration of carbon monoxide present in the air sample is graphically recorded by the analyzer on a moving paper chart.

In the hopcalite cell any carbon monoxide in the sample air starts action of a thermocouple which steps up a current. Then a bridge galvanometer actuates a carriage with motive power from a synchronous motor. The carriage operates 6 contact disks which, in turn, control the fans. This carriage also carries a pen which registers on a roll chart. The concentrations of carbon monoxide and the corresponding fan operation are given in table 3.

A selector switch enables the fans to be controlled either automatically or manually. When the selector switch is set to operate automatically, the automatic recorders have full control of the fans. When the switch is set for manual operation there is partial automatic control and when it is in the off position there is full manual control.

TABLE 3.—*Fan operation for various concentrations of carbon monoxide in the Wawona tunnel*

Parts of carbon monoxide per 10,000 parts of air	Fan operation		
	Number operating	Speed	Capacity
		R. p. m.	*Cu. ft. per min.*
0.49			
0.5	1	200	50,000
1.0	2	200	100,000
1.5	3	200	150,000
2.0	1	400	100,000
	2	200	100,000
2.5	1	200	50,000
	2	400	200,000
3.0	3	400	300,000

A more detailed description of the analyzers and the switch controls follows:

The whole sampling operation is accomplished with the equipment shown in figure 27 by passing the sample of air through a charcoal trap and a sulphuric acid bath where dust, dirt, and moisture are removed. The sample next passes through a filter tower of alternate layers of charcoal, cotton, and glass wool, where acid spray and other impurities are removed. The sample continues on through a soda, lime, and charcoal cannister that neutralizes or filters out any remaining acid fumes, gases, and impurities. The sample now passes into the flow meter where it is regulated to a continuous volume of 48 liters per minute. The regulation is automatic, since any increase in resistance to the left of the capillary orifice is transmitted to the right of the capillary tube, through the water head reservoir, water cylinder, and bubbling tube. Raising or lowering the bubbling tube changes its hydrostatic head in the water cylinder, which proportionately changes the air flow by bubbling out surplus sample air to the atmosphere. The sample next passes through a calcium chloride drying tube that removes any moisture picked up in the flow meter. (See fig. 27.)

The prepared sample then passes through a tubular heating coil immersed in the steam bath where it is warmed before entering the hopcalite cell for analysis. The hopcalite cell is also immersed in the bath, permitting the thermocouple to generate a continuous normal current. The bath is maintained at a constant uniform temperature of 208 degrees F.[12] by an electric heating element, assisted by an air-cooled condenser which removes resulting steam. The thermocouple contains 36 joints, half of which are imbedded in active hopcalite and form the hot pole, while the other half are imbedded in inert pumice and form the cold pole. The sample of air, in passing through the cell, comes in contact with the hopcalite, and any carbon monoxide present in the sample sets up a catalytic oxidation, the intensity of which is proportional to the concentration. The resultant heat reacts on the hot joints of the thermocouple, causing the generation of an electric current, the intensity of which is proportional to the degree of heat developed by the catalytic oxidation. The current thus generated in the hot pole is conducted through a bridge galvanometer, where it is measured in millivolts and returned to the cold pole, completing the circuit.

The thermocouples of the analyzers are connected to the galvanometers of their respective recorders through a bridge or split potentiometer circuit as shown in figure 27. The circuit is electrically balanced through the medium of rheostat R1 and potentiometers P1–P2, until that portion of the dry-cell current equals the normal current generated in the thermocouples by the heat action of the steam bath. When the circuit is thus in electrical balance, there will be no flow of current through the galvanometer; however, when catalytic oxidation occurs and generates a current of higher value than the normal current, the electrical balance will be upset and cause the galvanometer proportionately to deflect from zero. The current of the electrical balance is established at the time of calibration of the analyzers. The electrical balance is checked or compared with this value every 30 minutes by the automatic closing of cam switch S1, which connects the standard or mercury cell into the circuit comparing the dry-cell voltage across resistances R2–R3–R4–R5, and compensating any differences by adjusting R1 and P1. The galvanometer draws about 10 millivolt-amperes for full scale deflection or registration of 10 parts of carbon monoxide. The dry-cell voltage of 1.5 volts is reduced to 1 volt through the rheostat R1. When the cell voltage drops to 1 volt the cell should be replaced. The standard, or mercury cell, is in the circuit only half a minute in every half-hour and should last indefinitely.

[12] This is above the boiling point of water at this elevation.

When concentrations are below 0.5 part, the pen carriage contacts, H1 to H6, are open and their associated C.L. contacts are closed, and relays R1 to R12 are de-energized as shown in figure 27. As concentrations increase and the pen carriage moves up the scale, the contact disks 1 to 6, progressively, open their C.L. contacts and close the associated H contact. Assume recorder A pen carriage to be moving up the scale closing contacts H1–H2–H3. As the contacts close, their respective operating coils Nos. 1–2–3 of low-speed relays R1–R2–R3 are energized and pull in, energizing in turn the operating coils L1–L2–L3 of line contactors R10–R11–R12, which "Y" connects the fan motors to 8 poles and operates them on low speed or 900 revolutions per minute. As the pen carriage continues up the scale and closes contacts H4–H5–H6, their associated operating coils Nos. 4–5–6 of high speed relays R7–R8–R9 are energized and pull in, dropping out the low speed relays and line contactors, and energizing the operating coils H1–H2–H3 of line contactors R10–R11–R12, which delta connects the fan motors to 4 poles and operates them on high speed or 1,800 revolutions per minute.

When the concentrations decrease and the pen carriage returns down scale, the "H" contact will open, first followed by the closing of its respective C.L. contacts. As the contacts C.L.6–C.L.5–C.L.4 close, the holding current of relays R9–R8–R7 through their contacts A1 will be by-passed around the operating coil through the C.L. contacts to the coil resistor and LX2, causing them to drop out and open the line contactors' high-speed operating coils, removing the motors from the line. As the high speed relays R9–R8–R7 open, the time delay relays R4–R5–R6 start and run through a pre-set time of 5 minutes, allowing the fans to coast down from 400 to 200 revolutions per minute, before permitting the low speed relays R1–R2–R3 to pull in and apply power to the motors for operation on low speed. If the pen carriage, in coming down the scale, closes the contacts C.L.3–C.L.2–C.L.1, before their respective time delay relays run out the time, the fans will coast on down to rest without going on low speed. The time delay relays are adjustable from 0 to 33 minutes and are used to prevent reactive current and strain on the fan blades. Recorder B is an exact duplicate of recorder A and controls the relays R1–R2–R3–R7–R8–R9 through the duplicate operating coils 1.1 to 6.1, which in turn control the same line contractors and time delay relays as did recorder A. The recorder registering the highest concentration takes precedence in governing the fans to that concentration.

At 48-hour intervals, the 8 pounds of sulphuric acid in the air-scrubbing train in the analyzer is renewed, and about 1 pint of water added. The chart rolls of the graphic recorders are replaced once a month. The drying tubes are repacked every 4 months with 2 pounds of anhydrous lump calcium chloride. The canister is refilled twice a year with a mixture of soda lime and charcoal. The charcoal trap and tower filter are refilled once a year with activated lump charcoal. The hopcalite cell is repacked twice a year with approximately 1.7 ounces of 14-mesh hopcalite and 0.48 ounce of 14-mesh pumice, after which it must be recalibrated. Pure carbon monoxide gas for calibrating the analyzers and recorders is manufactured in the control room by slowly dripping formic acid on hot sulphuric acid. Electric lamps last for about 1,800 hours of burning and are replaced as they burn out; reflectors are washed twice a year.

VENTILATING AND LIGHTING COST DATA GIVEN

The motor grouping switch is manually controlled and has three positions. When set on the first position fan No. 1 comes on first followed by Nos. 2 and 3. When set on the second position fan No. 2 comes on first followed by Nos. 3 and 1. When set on the third position fan No. 3 comes on first followed by Nos. 1 and 2. The switch is shifted to a new position once a week, thus distributing the wear on the fans and motors, otherwise, one or two fans would receive most of the wear.

Each portal is equipped with a semaphore traffic warning signal which automatically drops to the stop

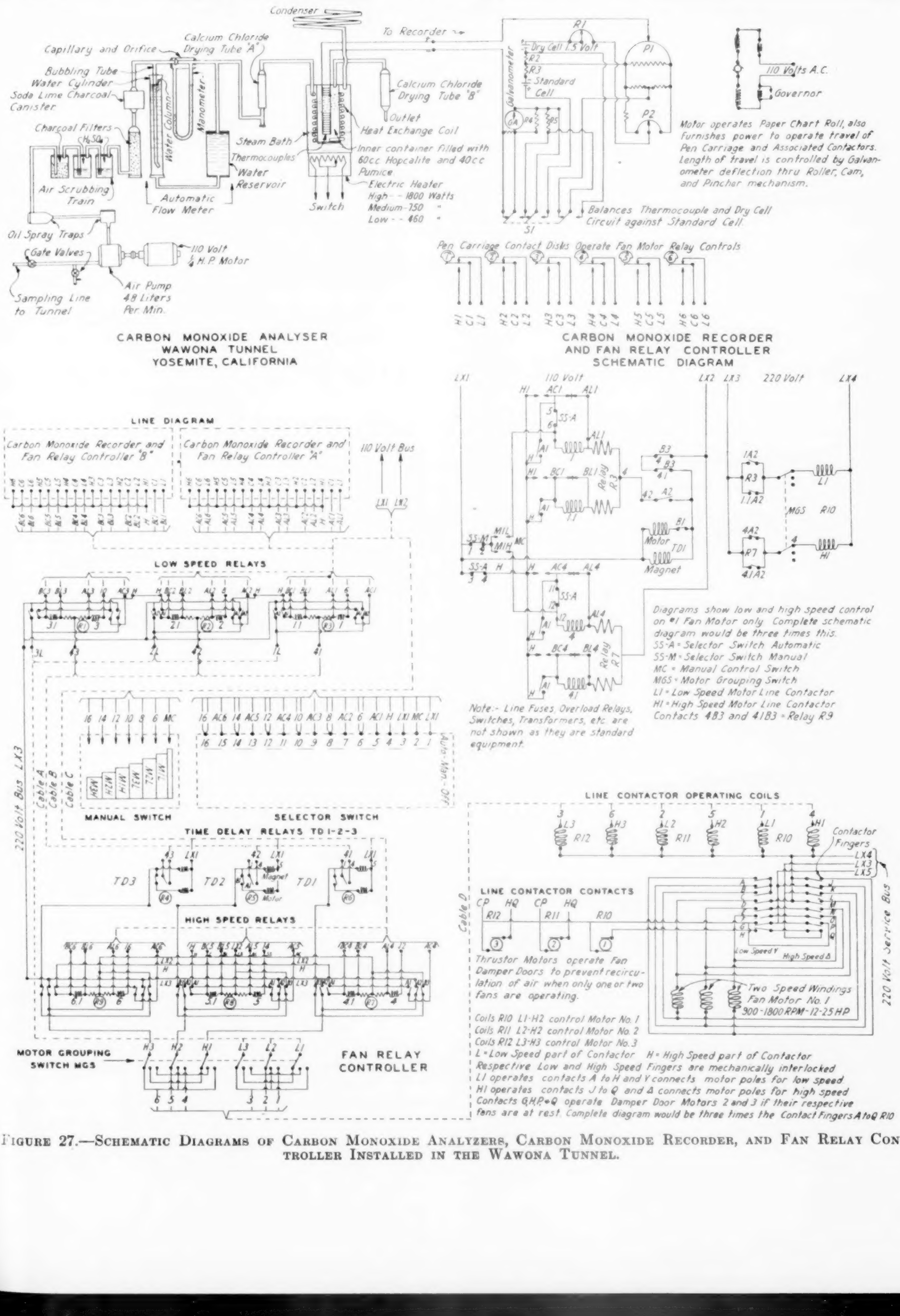

FIGURE 27.—SCHEMATIC DIAGRAMS OF CARBON MONOXIDE ANALYZERS, CARBON MONOXIDE RECORDER, AND FAN RELAY CONTROLLER INSTALLED IN THE WAWONA TUNNEL.

position if carbon monoxide concentrations become excessive. Telephones are installed at each portal and in the center adit. They all are connected to the National Park Service switchboard in Yosemite National Park and provide a means of communication when necessary.

Electrical energy for light and power is supplied by a hydroelectric plant at 2,300 volts, 60 cycles, 3-phase. It is transmitted to the tunnel through an overhead transmission line carried on steel poles. The transmission line is of considerable interest. It is approximately 8,000 feet long and has numerous spans of 400 to 600 feet between poles. One span is 1,200 feet long, with a difference in elevation of supports of 850 feet. A control room located in the central, or fan adit, houses the analyzers, recorders, switchboard, transformers, etc. The total load is 98.6 kilowatts, distributed as follows:

	Kilowatts
Tunnel lighting	32. 1
Ventilation	57. 5
Analyzers, recorders	6. 5
Signals, relays, controls	2. 5
Total	98. 6

Inspection of all the apparatus is made every 48 hours.

The necessity of artificial ventilation to augment natural draft is borne out in table 4 which shows carbon monoxide gas concentrations and traffic data for a 12-hour period on May 30, 1937.

TABLE 4.—*Carbon monoxide gas concentrations and traffic data for a 12-hour period on May 30, 1937 (Wawona tunnel)*[1]

Time	Carbon monoxide in parts per 10,000 parts of air	Traffic
6 to 7 a. m.	0. 3	125
7 to 8 a. m.	. 4	200
8 to 9 a. m.	. 5	175
9 to 10 a. m.	3. 3	250
10 to 11 a. m.	5. 6	350
11 to 12 m.	4. 4	500
12 to 1 p. m.	3. 5	558
1 to 2 p. m.	6. 1	615
2 to 3 p. m.	3. 6	820
3 to 4 p. m.	3. 9	737
4 to 5 p. m.	2. 0	610
5 to 6 p. m.	2. 6	400
Average or total	3. 0	5, 340

[1] Total power consumption for ventilation, lights, etc. for 24-hour period was 1,150 kilowatt-hours.

The total construction cost of the tunnel amounted to $563,729.31. Of this amount, $39,693.33, or 7 percent, was expended for ventilation and lighting equipment distributed as follows:

Carbon monoxide analyzers, recorders, etc	$10, 061. 49
Ventilation fans, motors, transformers, etc	8, 394. 95
Lighting units, transformers, conduits, etc	6, 440. 89
Automatic switchboard, relays, controls, etc	2, 184. 00
Telephones, cable transmission line	1, 913. 00
Warning signals, devices, cable, etc	1, 555. 00
2,300 volt transmission line, power panel, etc	9, 144. 00
Total	39, 693. 33

The estimated traffic for the last 11 months of 1936 was 167,830 vehicles and the operating cost amounted to $4,624.45, distributed as shown in table 5.

The estimated traffic for the first 6 months of 1937 was 102,993 vehicles and the operating cost amounted to $1,964.45, distributed as shown in table 6.

TABLE 5.—*Power consumption and operation costs for lighting and ventilating Wawona tunnel, last 11 months of 1936*

Month	Power consumption for lighting and ventilation	Cost [1]
	Kilowatts	
February	13, 080	$196. 20
March	10, 700	160. 50
April	22, 360	335. 40
May	26, 810	402. 15
June	25, 270	379. 05
July	26, 240	393. 60
August	26, 220	393. 30
September	23, 020	345. 30
October	11, 870	178. 05
November	3, 680	55. 20
December	4, 580	68. 70
Total	193, 830	[2] 2, 907. 45

[1] At $0.015 per kilowatt-hour.
[2] The cost of inspection, maintenance, and repairs (labor) was $1,609; the cost of material and supplies was $108; making a total cost of $4,624.45.

TABLE 6.—*Power consumption and operation costs for lighting and ventilating Wawona tunnel, first 6 months of 1937*

Month	Power consumption for lighting and ventilation	Cost [1]
	Kilowatts	
January	14, 270	$214. 05
February	10, 460	156. 90
March	11, 420	171. 30
April	12, 290	184. 35
May	21, 300	319. 50
June	23, 890	358. 35
Total	93, 630	[2] 1, 404. 45

[1] At $0.015 per kilowatt-hour.
[2] The cost of inspection, maintenance, and repairs (labor) was $500; the cost of material and supplies was $60; making a total cost of $1,964.45.

INDEX TO PUBLIC ROADS, VOLUME 18, NOW AVAILABLE

The index to volume 18 of PUBLIC ROADS is now available. In addition to the index a chronological list of articles and a list of authors are given. The index will be sent free to subscribers to PUBLIC ROADS requesting it. Requests should be addressed to the Bureau of Public Roads, United States Department of Agriculture, Washington, D. C.

Indexes to volumes 6 to 17, inclusive, are also available and will be sent to PUBLIC ROADS subscribers upon request. Indexes to volumes 1 to 5, inclusive, have never been prepared and it is not expected that these volumes will ever be indexed.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF AUGUST 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 1,357,201	$ 584,800	5.9	$ 8,004,638	$ 3,994,190	335.8	$ 2,217,394	$ 1,106,105	91.5	$ 3,065,095
Arizona	104,551	75,048	6.2	1,660,552	1,258,667	89.3	381,819	243,878	17.4	1,598,412
Arkansas	377,609	375,996	34.9	396,276	395,543	39.6	3,081,724	3,076,222	185.2	1,117,172
California	1,836,771	963,565	65.8	10,413,202	5,459,857	174.5	3,322,421	1,789,424	74.8	1,782,781
Colorado	973,999	534,844	41.7	2,514,863	1,384,056	68.4	1,453,171	807,562	41.1	2,002,388
Connecticut				1,350,040	660,511	14.7	244,930	120,990	2.1	1,536,794
Delaware	54,130	27,065		782,314	385,679	22.2	480,998	241,791	1.4	1,184,277
Florida	384,200	192,100	14.9	3,381,738	1,690,869	70.6	1,768,070	609,435	9.6	2,853,512
Georgia	2,168,089	1,084,044	106.0	6,488,144	3,244,072	309.5	900,870	450,435	50.4	5,518,798
Idaho	1,068,410	636,730	80.7	1,855,713	1,105,107	137.2	216,751	129,578	10.1	1,124,736
Illinois	1,056,000	548,784	32.7	10,548,238	5,268,705	223.0	4,608,150	2,304,074	125.6	2,385,638
Indiana	1,378,350	689,175	38.0	5,316,367	2,652,215	126.0	1,444,800	722,270	26.0	2,537,966
Iowa	1,367,372	628,196	40.4	8,023,334	3,625,683	255.7	1,354,467	635,823	46.7	744,447
Kansas	652,039	326,019	28.9	5,534,428	2,723,421	606.8	4,763,678	2,381,830	344.1	2,865,792
Kentucky	1,221,362	597,939	67.0	4,824,260	2,412,130	134.2	2,788,148	1,394,074	79.0	2,021,125
Louisiana	256,047	128,000	9.3	12,055,777	2,401,505	57.1	1,911,582	853,091	30.7	2,338,123
Maine	1,250,300	625,084	32.6	1,633,946	809,683	33.1	1,062,224	531,111	17.8	284,541
Maryland	308,000	154,000	5.4	1,683,567	840,021	25.4	1,230,411	602,830	18.1	1,992,916
Massachusetts	122,568	61,284	.8	2,676,060	1,338,026	10.0	566,703	283,350	8.6	2,666,105
Michigan	1,729,700	864,850	58.1	7,267,508	3,562,569	141.6	1,736,044	863,117	34.7	1,849,945
Minnesota	539,480	243,094	12.2	5,434,998	2,701,243	293.6	3,276,776	1,630,237	150.3	2,274,026
Mississippi	486,408	216,262	24.2	8,465,880	3,350,131	375.7	1,476,500	390,710	70.2	3,196,842
Missouri	980,863	488,227	37.1	4,948,747	2,429,616	125.4	3,769,827	1,562,684	141.5	3,619,521
Montana	641,438	360,798	28.8	1,107,172	622,419	42.0	506,495	284,901	20.5	4,344,969
Nebraska	1,403,437	701,323	170.2	6,527,170	3,253,984	503.7	2,354,962	543,930	71.2	2,593,404
Nevada	892,813	773,286	79.8	810,627	697,031	101.4	215,060	186,495	4.5	1,437,152
New Hampshire	274,331	135,489	9.2	925,230	461,067	13.8	185,865	92,914	3.0	1,135,339
New Jersey				2,852,361	1,424,918	21.2	211,060	104,010	.5	2,672,543
New Mexico	1,157,176	705,751	145.4	1,423,518	967,881	93.9	704,592	429,729	32.2	779,236
New York	2,119,953	1,030,620	46.7	16,752,376	8,165,917	288.4	2,286,020	1,084,690	26.4	2,950,798
North Carolina	1,725,948	894,015	109.7	6,621,886	3,152,399	294.4	1,923,140	950,440	119.4	2,373,394
North Dakota	2,590	2,590		2,687,171	2,551,245	189.5	830,942	608,893	78.5	3,569,866
Ohio	1,976,430	986,180	26.7	8,242,462	4,092,820	86.4	4,514,690	2,247,018	36.6	6,578,536
Oklahoma	1,371,102	722,664	67.6	5,534,804	2,887,882	176.8	1,642,937	871,146	69.9	2,878,134
Oregon	940,773	524,235	43.6	1,898,758	1,126,214	47.7	352,233	214,990	10.6	2,135,486
Pennsylvania	2,290,471	1,144,186	41.8	6,245,748	3,100,327	90.2	5,993,753	2,993,682	57.7	3,595,333
Rhode Island	202,800	101,400	1.7	939,242	469,621	14.2	301,760	150,880	2.1	1,021,899
South Carolina	1,832,002	819,493	86.1	3,860,502	1,708,331	171.0	1,280,056	589,300	59.4	1,660,984
South Dakota	195,110	115,760	22.9	4,055,762	2,245,790	364.9	1,360,930	751,310	119.1	3,037,872
Tennessee	1,011,340	505,670	37.4	5,056,894	2,528,447	142.3	706,320	353,160	12.4	4,601,818
Texas	4,921,271	2,439,928	318.1	10,518,144	5,215,042	554.4	3,692,287	1,680,518	216.1	7,049,767
Utah	463,180	332,070	67.8	1,275,370	912,270	59.5	668,200	472,350	30.4	1,096,433
Vermont	739,709	324,451	20.3	1,051,840	501,258	28.8	193,250	96,430	4.0	216,361
Virginia	1,368,645	684,322	52.9	5,276,584	2,635,771	174.3	1,920,501	957,721	49.8	760,705
Washington	1,289,826	683,301	26.2	3,349,150	1,753,230	49.4	993,509	521,000	18.4	1,050,896
West Virginia	115,250	92,300	9.2	2,251,333	1,488,565	62.6	784,989	398,438	17.6	2,249,918
Wisconsin	1,878,871	904,877	52.4	6,700,520	3,089,640	192.8	1,685,881	774,190	57.7	1,524,979
Wyoming	584,300	358,877	62.9	1,694,734	1,040,706	215.0	137,200	84,760	18.0	788,145
District of Columbia										
Hawaii	369,705	184,853	6.6	812,825	397,342	15.1	492,600	243,940	5.5	1,199,041
Puerto Rico				1,128,739	562,390	20.5				671,985
TOTALS	49,441,920	25,573,545	2,276.8	224,861,512	110,746,006	7,683.6	79,996,690	40,417,456	2,718.4	114,535,945

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF AUGUST 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama				$ 452,600	$ 226,150	30.3	$ 192,005	$ 94,750	13.7	$ 732,072
Arizona	$ 61,871	$ 32,500	3.5	134,185	96,508	7.9	130,629	86,340	9.2	441,134
Arkansas				19,426	12,863					851,245
California	281,757	161,895	20.8	972,288	523,189	54.4	750,036	405,386	22.1	754,463
Colorado	303,280	168,620	17.0	482,446	266,673	29.0	138,040	59,610	9.9	426,665
Connecticut				27,460	13,730	.7	60,470	30,035	.7	274,513
Delaware							64,910	32,455	12.2	214,420
Florida				20,122	10,061					664,791
Georgia	121,120	60,560	16.2	256,858	128,429	33.0	524,497	262,249	64.0	807,484
Idaho	105,529	52,041	8.0	306,582	133,830	32.7	71,984	23,880	13.9	263,821
Illinois	186,000	93,000	21.6	1,664,832	778,416	126.1	832,500	416,250	53.2	739,249
Indiana				780,900	334,750	80.3	978,188	485,850	90.5	421,838
Iowa										1,298,449
Kansas	43,670	21,835	.5	61,294	30,647	.8	250,786	125,392	42.2	1,141,097
Kentucky	309,086	104,551	52.0	524,798	147,811	37.5	1,395,013	385,048	107.8	177,016
Louisiana				36,459	18,135	.8	826,749	343,720	73.6	362,281
Maine	144,600	72,300	9.8	287,726	143,863	17.6	224,400	105,833	9.3	6,577
Maryland				6,263	3,132					409,344
Massachusetts				5,300	2,650		72,710	36,355	1.4	607,395
Michigan				262,966	131,483	24.9	518,500	259,250	36.6	1,144,806
Minnesota	64,876	32,438		344,684	160,286	45.4	142,000	70,670	6.7	1,116,186
Mississippi							317,100	158,500	23.8	730,427
Missouri	189,646	94,630	32.5	246,050	122,635	14.1	557,150	192,825	76.8	654,998
Montana				13,983	7,865					1,027,170
Nebraska	132,830	66,415	17.7	414,998	207,499	64.6	221,782	101,575	44.1	620,563
Nevada	116,610	101,122	11.4	190,090	164,472	30.7	131,727	112,784	44.4	113,834
New Hampshire	97,426	48,277	1.7	111,335	55,301	2.8	39,820	19,880	1.5	123,417
New Jersey				71,490	35,745	1.8	284,710	137,260	3.3	499,768
New Mexico	289,750	176,717	14.4	251,644	153,476	16.3	232,359	132,233	17.2	344,346
New York	699,960	349,980	48.8	1,854,700	911,350	122.5	667,500	321,750	40.1	776,193
North Carolina	29,080	14,540	7.6	910,184	455,070	90.0	213,560	89,720	13.8	522,525
North Dakota				106,900	57,253	26.8	91,100	48,792	16.2	681,207
Ohio				184,400	92,200	3.8	11,100	5,000	.9	1,734,441
Oklahoma				242,508	129,034	16.7	587,110	292,473	45.3	763,408
Oregon	103,929	62,390	15.8	286,593	174,172	31.4	101,414	52,970	13.4	463,590
Pennsylvania	397,444	194,077	28.3	1,325,920	637,768	86.9	1,023,708	511,854	54.0	772,189
Rhode Island	21,730	10,865	.6	113,958	56,979	5.5	56,690	28,345	1.4	91,702
South Carolina				543,081	230,762	61.6	681,685	278,854	69.6	169,064
South Dakota				11,300	6,250					816,436
Tennessee				314,586	157,293	13.1	399,180	138,940	23.4	763,257
Texas	357,714	162,388	73.2	1,810,549	851,769	212.0	1,174,294	448,250	138.1	1,662,362
Utah	70,870	39,550	7.8	339,420	188,770	30.5	175,880	76,960	25.0	245,090
Vermont	163,580	71,150	9.7	84,476	40,703	4.1	76,700	35,450	3.2	62,293
Virginia	108,500	54,250	16.1	648,587	292,883	42.4	384,010	168,304	39.3	376,562
Washington	153,583	80,800	10.6	383,482	201,378	48.2	393,268	207,000	26.6	241,378
West Virginia				244,050	122,025	21.4	82,300	41,150	4.5	386,499
Wisconsin				695,138	331,395	26.7	395,090	191,170	24.2	689,663
Wyoming	290,340	179,400	33.7	149,580	92,420	15.2	235,700	145,650	15.7	167,723
District of Columbia										
Hawaii				56,250	28,125	2.4				218,750
Puerto Rico				244,000	121,950	13.7				124,925
TOTALS	4,844,781	2,506,291	479.3	18,496,441	9,089,148	1,526.6	15,708,354	7,160,762	1,332.8	28,698,626

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SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

UNIFORM VEHICLE CODE

Act I.—Uniform Motor Vehicle Administration, Registration, Certificate of Title, and Antitheft Act.

Act II.—Uniform Motor Vehicle Operators' and Chauffeurs' License Act.

Act III.—Uniform Motor Vehicle Civil Liability Act.

Act IV.—Uniform Motor Vehicle Safety Responsibility Act.

Act V.—Uniform Act Regulating Traffic on Highways.

Model Traffic Ordinances.

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U. S. Bureau of Public Roads, Willard Building, Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF AUGUST 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
			NUMBER					NUMBER					NUMBER			
	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama	$ 127,900	$ 127,900	3			$ 451,948	$ 450,924	5			$ 598,910	$ 598,410	6		7	$ 808,285
Arizona						4,718	4,718									625,495
Arkansas						366,437	365,280	8			273,650	273,119	6			1,120,370
California	106,025	106,025		1		1,235,726	1,235,151	4	3		325,621	316,149	3			2,042,884
Colorado	18,855	18,855	1		1	71,588	71,588	1			11,776	8,016			3	1,189,583
Connecticut																844,490
Delaware											77,270	77,270			23	416,480
Florida						10,616	10,616				178,800	178,800	1			1,216,381
Georgia						18,346	18,346				68,200	68,200	3			2,330,841
Idaho	87,825	87,652	1			12,342	12,342				85,392	85,392	3			637,484
Illinois	4,500	4,500			1	1,471,675	1,471,675	6			806,230	806,230	6	1	60	2,922,238
Indiana	269,886	183,900		3		600,600	573,700	5	2		689,780	689,780	1	1	89	966,769
Iowa	521,482	493,000	4		8	496,933	468,200	6	1	6	231,712	216,600	1		7	1,384,766
Kansas	196,494	196,494	6		4	510,094	508,094	6			489,095	489,095	7		4	1,380,825
Kentucky						145,000	145,000	1			515,416	515,416	4	1	31	1,153,629
Louisiana						146,486	146,478	2			327,021	293,050	6			1,137,543
Maine						414,697	414,697	5	2		2,610	2,610			1	273,896
Maryland						64,586	64,586	1								962,247
Massachusetts						70,420	70,420		1		214,320	210,919	1	1		1,631,949
Michigan	110,000	110,000	1	1		886,558	886,558	5		45	566,600	566,600	8	1		1,722,027
Minnesota	40,218	40,218		1	1	777,076	777,076	3	5							1,604,188
Mississippi						355,700	355,700	4								1,228,451
Missouri	66,460	66,460	1	1		285,630	285,630	3			55,560	55,560	1			2,617,603
Montana						642,268	637,386	6			175,365	175,365	2			511,720
Nebraska						325,663	325,663	13			15,264	15,264			7	1,423,483
Nevada	5,626	5,626			2	91,561	91,561		2		57,561	57,561		1	2	303,893
New Hampshire	61,732	61,425		1		7,406	7,406									424,919
New Jersey						210,005	204,779	2	1		15,630	15,630			2	1,749,848
New Mexico						122,441	122,441	4			206,032	206,032	3	1		523,018
New York	130,400	130,400		1		1,929,559	1,923,008	8	5	2	344,963	343,963		2		4,372,558
North Carolina						504,760	504,760	4	2		518,620	463,620	3	6	7	1,476,014
North Dakota						559,858	559,858	1	2		46,420	46,420	1			972,943
Ohio						103,830	103,830	2			195,400	195,400	2			3,929,938
Oklahoma						17,343	17,343				36,075	36,075			13	2,228,091
Oregon	95,263	94,614		2		220,687	220,687	1			9,754	9,754				650,276
Pennsylvania						299,116	283,910	2			200,021	191,000	1			5,257,625
Rhode Island						231,303	231,303	1			159,638	159,638		3		102,809
South Carolina						86,379	63,593	1	2		140,075	140,075			34	1,285,434
South Dakota	3,870	3,870			1	312,558	310,418	2	2	6	114,070	112,670	5		3	891,799
Tennessee						14,381	14,381				87,380	87,380		2	1	1,790,272
Texas	36,660	35,990	2	.		780,122	780,122	7	1		403,217	402,605	4	2		4,123,072
Utah	1,160	1,760			1	122,518	122,518	3			25,400	25,400	1		3	423,385
Vermont	175,382	170,382	4	1		54,954	54,954	2	1		18,220	18,220			7	236,571
Virginia	120,290	120,290	9	1		289,578	289,578	4	1		164,440	164,440	3		8	1,221,722
Washington	92,233	90,133		2	2	687,331	687,331	8	2		17,162	17,162			2	589,174
West Virginia						412,009	410,989	4			37,470	37,470			5	875,639
Wisconsin	100,586	100,586	1			1,032,228	1,015,047	9			151,644	145,856	3			1,212,020
Wyoming						159,644	159,644		2		14,530	14,530			6	502,556
District of Columbia																325,431
Hawaii						33,230	33,230	1			163,920	163,920	2	1		296,600
Puerto Rico						110,940	110,390	3			116,096	115,440	1			504,470
TOTALS	2,373,447	2,250,080	33	15	21	17,758,848	17,622,909	153	37	59	8,952,330	8,812,106	88	23	325	66,423,704